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PROCEEDINGS OF THE CONFERENCE ON SPACE AND MILITARY APPLICATIONS OF AUTOMATION AND ROBOTICS

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AND THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA 35898-5222

21-22 JUNE 1988

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U.S. ARMY
MISSILE COMMAND

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

These proceedings contain the papers presented at the Conference on Space and Military Applications of Automation and Robotics held 21-22 June 1988 in Huntsville, Alabama. The conference sessions were arranged to present two concurrent programs. Welcome speeches and the keynote addresses were given at the Plenary Session. Twelve topical sessions covered current areas of interest in automation and robotics technology. Papers presented at the session entitled IVA Robotics addressed robotics applications aboard the Space Station. In the session entitled Strategies for Deployment, robotics systems for battlefiedl automation and reconnaissance/surveillance missions were discussed. The conference program included two sessions on Artificial Intelligence and Expert Systems. Papers in these sessions covered a variety of topics including undersea remotely operated vehicles, autonomous land vehicles, autonomous aircraft, telerobotics, modeling and simulation, sensor fusion, programming languages and man machine interfaces. The Sensors and Image Processing session papers addressed laser radar, multimode trackers for fire and forget systems, image stabilization (OVER)

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techniques for robotic vehicles and digital image processing. There were also two sessions on Robotic Systems. These papers discussed methods and technology of existing robot systems. Papers presented at the session entitled Guidance, Navigation and Control addressed guidance and control systems for autonomous land vehicles, control systems for automated refueling systems and use of mobile robots in toxic environments. Feasibility studies, design guidelines, operational constraints, safety aspects and performance analysis of telerobotic systems were subjects of papers presented at the Telerobotics session. Finally, there were three sessions on Manufacturing of Aerospace and Missile Systems included in the conference program. Papers were presented on robot assembly systems, robotic test cells CAD/CAM systems, control systems for welding robots, expert process development and simulation of industrial/manufacturing systems.

(KR)

GACIAC PR 88-02 JUNE 1989

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FOREWORD

CONFERENCE ON SPACE AND MILITARY APPLICATIONS OF AUTOMATION AND ROBOTICS (A&R)

21 - 22 JUNE 1988

The idea to sponsor a joint conference between the U.S. Army Missile Command and the NASA Marshall Space Flight Center evolved between the two agencies during exchanges of information related to automation and robotics (A&R). Program A consisted of mostly NASA related topics while Program B consisted of mostly Army topics. In some instances topics from both agencies were included in the same session. There were enough similarities in the emerging technologies for an exchange of ideas to take place; however, as the conference progressed an interesting difference in the motivations for A&R research within the two agencies became apparent. While both space and the battlefield are volatile environments to people, Army technologies are moving forward to remove people from the battlefield while NASA technologies are moving forward to station people in space.

A similarity between both agencies is their concern for finding ways to develop high technology systems that will enhance human capabilities and conserve resources. The conference identified some of the problems and solutions addressing the challenges that exist today. Future requirements were also defined.

Dr. Robert J. Heaston
GACIAC Director

CONFERENCE ON SPACE AND MILITARY APPLICATIONS
OF AUTOMATION AND ROBOTICS

21-22 JUNE 1988

MARRIOTT OF HUNTSVILLE, ALABAMA

Technical Pr ram Chairman:	Dr. Gary L. Workman University of Alabama in Huntsville
General Chair:	Elaine Hinman NASA/MSFC
	J. L. Prater USAMICOM/RDEC
Plenary Session:	Elaine Hinman NASA/MSFC
	J. L. Prater USAMICOM/RDEC
Welcoming Remarks:	J. R. Thompson, Director NASA/MSFC
	W. C. McCorkle, Director USAMICOM/RDEC
NASA Keynote:	J. B. Odom Associate Administrator for the Space Station NASA Headquarters
Army Keynote:	J. D. Weisz, Director Human Engineering Laboratories LABCOM
Plenary Presentation:	Steve Bartholet Odetics, Inc.

Monday, June 20, 1988

06:00 - 08:00 PM Pre-Registration in Marriott Lobby Area

Tuesday, June 21, 1988

07:30 - 08:30 AM Registration (lobby)

08:00 - 10:00	Plenary Session I Chairs: Elaine Hinman, NASA/MSFC J.L. Prater, USAMICOM/RDEC
08:05	Welcoming Remarks: J.R. Thompson, Director, NASA/MSFC Col. Nicholas Hurst, Deputy Director, USAMICOM/RDEC
08:25	NASA Keynote: J.B. Odom, Deputy Director for the Space Station NASA HQ
08:55	Army Keynote: J.D. Weisz, Director, Human Engineering Laboratories LABCOM
09:35	Plenary Presentation: Steve Bartholet, Odetics, Inc.
10:15	BREAK
10:30	Session II Program A IVA Robotics Chair: Pam Nelson, NASA/MSFC
Keynote:	W.B. Chubb, Director, Information and Electronic Systems Laboratory, MSFC

"Dual-Arm Robot for Telerobotic IVA Operations on the Space Station"
M.C. Ziemke, H.M. Chang, University of Alabama in Huntsville
J. Kader, Kader Robotics, Inc.

"The Impact of an IVA Robot on the Space Station Microgravity Environment"
P.E. Harman, Teledyne Brown Engineering
D.A. Rohn, NASA/Lewis Research Center

"An Automated Protein Crystal Growth Facility on the Space Station"
M.C. Herrmann, NASA/MSFC

10:30	Session II Program B Strategies for Deployment Chair: J.L. Prater, USAMICOM/RDEC
Keynote:	Colonel J.D. Petty, Director Advanced System Concepts Office

"TMAP - The Army's Near Term Entree to Battlefield Robotics"
R.K. Simmons, Martin-Marietta Baltimore

"When Will Robots Be Used in Combat?"
S.Y. Harmon, Robot Intelligence International

"TMAP: An Offset Platform"
J. Kirsch, Grumman Corporation

12:00	LUNCH (served poolside)
01:30	Session III Program A Artificial Intelligence and Expert Systems I Chair: Elaine Hinman, NASA/MSFC

"An Expert System for Object Recovery"
A. Farsaie and T.A. Dumoulin, Naval Surface Weapons Center
W.A. Venezia, Naval Surface Warfare Center

"High Level Intelligent Control of Telerobotic Systems"
J.W. McKee, University of Alabama in Huntsville, and
J. Wolfsberger, NASA/MSFC

"Neutral File Data Exchange Between Simulators and Robots"
W.D. Engelke, University of Alabama in Huntsville

"Cooperating Expert Systems"
M. Brady and D.R. Ford, University of Alabama in Huntsville

"Space Languages"
S. Davis and D. Hayes, University of Alabama in Huntsville
J. Wolfsberger, NASA/MSFC

01:30 Session III Program B
Sensors and Image Processing
Chair: Lynn Craft, MICOM

"A System for High Resolution 3D Mapping Using Laser Radar and Requiring No Beam Scanning Mechanisms"
P. Rademacher, Robotic Vision Systems, Inc.

"Technology Transfer: Imaging Tracker to Robotic Controller"
W.S. Otaguro, L.O. Kesler, McDonnell Douglas Astronautics Co.
K.C. Land, H. Erwin, and D.E. Rhoades, NASA/Johnson Space Center

"Stabilized Image System for Mobile Robots"
D.S. Stauffer and E. Watts
Rexham Aerospace and Defense Group

"Two Dimensional Convolute Integer Technology for Digital Image Processing"
T.R. Edwards, TREC, Inc.

03:15 BREAK

03:30 Session IV Program A
Robotic Systems
Chair: Chuck Shoemaker, Human Engineering Laboratory

"A New Approach to Robot Kinematic Analysis"
M.S. Waggener and F.J. Testa
Advanced Control Technologies, Inc., and
G.O. Beale, George Mason University

"Omnicon - The Self-Aligning Space Connector"
H.S. Harman, Environmental Components, Inc.

"Fluid Disconnects for Automated and Robotic Spacecraft Servicing"
J.M. Cardin, Moog Incorporated

"Development of a Hybrid Simulator for Robotic Manipulators"
P.M. Van Wirt and M.B. Leahy, Jr.,
Air Force Institute of Technology

03:30 Session IV Program B
Guidance, Navigation and Control
Chair: Greg Graham, USAMICOM

"The DARPA Autonomous Land Vehicle: A Phase I Retrospective and a Prospective for the Future"
R.J. Douglass, Martin-Marietta Denver

"Development of a Man-Portable Control Unit for a Teleoperated Land Vehicle"
D.E. McGovern and S.V. Spires, Sandia National Laboratories

"Robotic Visual Servo Control for Aircraft Ground Refueling"
M.M. Miller, M.B. Leahy, Jr., and M. Kabrisky, Air Force Institute of Technology

"Use of Mobile Robots in Responding to Radiological and Toxic Chemical Accidents"
H.B. Meieran, PHD Technologies, Inc.

"The Versatool III"
F.R. Skinner, Robo-Tech Systems

05:30 - 07:30 Reception (Marriott Ballroom)
Chair: G.L. Workman, University of Alabama in Huntsville

Speaker: Joe Engelberger, TRC, Inc.

Wednesday, June 22, 1988

08:00 AM — Session V Program A
Robotic Systems
Chair: Ken Fernandez, NASA/MSFC

Keynote: J.W. Littles, Director, Science and Engineering, MSFC

"Insertion with Two Coordinated Robot Arms"
F.L. Swern and S.J. Tricamo, Stevens Institute of Technology
N.P. Coleman, Jr U.S. Army R&D Center

"Orbital Maneuvering Vehicle (OMV) Remote Servicing Kit"
N.S. Brown, NASA/MSFC

"Inflatable End Effector Tools"
C.K. Lord, Olis Engineering, Inc.

08:00 AM — Session V Program B
Manufacturing of Aerospace and Missile Systems I
Chair: Howard Race, USAMICOM

Keynote: R.E. Bowles, Chief of Mobility of Technology Planning and Management, LABCOM

"Robotic Assembly of Microscopic Components in Millimeter Wave Devices"
S.A. Prokosch and K. Aufderhar, Honeywell, Inc.

"Automated Millimeter Wave (MMW) Transducer Testing in a Robotic/Vision Test Cell"
M. Francis and J. Risendal, Honeywell, Inc.
R. Hill, U.S. Army AMCCOM, Armament Research Development and Engineering Center

"Development of an Integrated CAD/CAM System for Wire Harness Fabrication"
J.M. Anderson, J.I. Locker, U.S. Army Missile Command
T.D. Morgan, L.C. Frederick and C.D. Minor, University of Alabama in Huntsville

10:15 — BREAK

10:30 Session VI Program A
Telerobotics
Chair: Cindy Coker, NASA/MSFC

"Testing the Feasibility of Using a Teleoperated Robot for Remote, Dexterous Operations"
J.A. Molino and L.J. Langley, Tech-U-Fit Corporation

"ORU Guidelines for Telerrobotic Compatibility"
M.M. Clarke and D. Manouchehri, Rockwell International

"Ground Control of Space Based Robotic Systems"
K.E. Farnell and S.F. Spearing, Teledyne Brown Engineering

"The Advanced Research Manipulator I"
P.D. Spidaliere, AAI Corporation

"Investigation of Learning Factors in the Performance of Teleoperated Tasks"
J.N. Lovett, Jr., University of Alabama in Huntsville
A.R. Wyskida and R.W. Amos, U.S. Army Missile Command

10:30 **Session VI Program B**
Manufacturing of Aerospace and Military Systems II
Chair: Chip Jones, NASA/MSFC

"Development of Automation & Robotics for Space via Computer Graphic Simulation Methods"
K. Fernandez, NASA/MSFC

"On Designing A Case-Based System for Expert Process Development"
S. Bharwani, J.T. Walls, and M.E. Jackson
Martin Marietta Laboratories

"Expert System Technology: An Avenue to an Intelligent Weld Process Control System"
R.E. Reeves, T.D. Manley, and A. Potter
General Digital Industries, Inc., and
D.R. Ford, University of Alabama in Huntsville

"Advantages of Off-Line Programming and Simulation for Industrial Applications"
J. Shiver, Martin Marietta Aerospace,
D. Gilliam and G.L. Workman, University of Alabama in Huntsville

12:00 Noon **Lunch (served poolside)**

01:30 Session VII Program A
Manufacturing of Aerospace and Military Systems III
Chair: J.M. Anderson, USAMICOM

"A 3-D Graphical Simulation of an Automated Direct Chip Probe/Test System"
D.C. Holderfield, U.S. Army Missile Command
T.D. Morgan, B.E. Martin, and J.A. Raney
University of Alabama in Huntsville

"Automated Manufacturing Programming System"
B.J. Schroer and F.T. Tseng
University of Alabama in Huntsville
J.W. Wolfsberger, NASA/MSFC

"Algorithm for Display of Automated Nondestructive Thickness Measurements"
J. van der Zijp, University of Alabama in Huntsville

01:30 Session VII Program B
Artificial Intelligence and Expert Systems II
Chair: Bernard Schroer, University of Alabama in Huntsville

"A Planner For Threat Assessment and Response"
A.N. Steinberg, The Analytic Science Corporation

"A Robotic Vehicle Route Planner for the 1990's"
W.J. Pollard, KMS Fusion, Inc.

"A Demonstration of Retro-Traverse Using a Semi-Autonomous Land Vehicle"
D.E. McGovern, P.R. Klarer, and D.P. Jones
Sandia National Laboratories

"Dynamic Planning for Smart Weapons"
S.J. Larimer and R.A. Luhrs, Martin-Marietta Denver

"A Knowlege Representation Scheme for a Robotic Land Vehicle Route Planner"
P.J. McNally, KMS Fusion, Inc.

"IRIS - An Intelligent Robot Insertion Expert System"
W. Teoh, Sparta, Inc.

"Pedagogical Issues in Developing a Man-Machine Interface for an Intelligent Tutoring System"
W.M. Holmes, USAMICOM

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CONFERENCE ON SPACE AND MILITARY APPLICATIONS
OF AUTOMATION AND ROBOTICS

ABSTRACTS

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PLENARY SESSION I

CHAIRS: Elaine Hinman, NASA/MSFC

and

J. L. Prater, USAMICOM/RDEC

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WELCOMING REMARKS

J. R. Thompson, Director
NASA/MSFC

and

W.C. McCorkle, Director *
USAMICOM/RDEC

* Presented by Col. Nicholas Hurst

James R. Thompson, Jr.
NASA HQ

Welcoming Speaker

James R. (J.R.) Thompson, Jr., was named director of the Marshall Center on September 29, 1986, after serving three years as Deputy Director (technical) at the Princeton University Plasma Physics Laboratory. In 1986, while still at Princeton, he was named vice-chairman and day-to-day head of the NASA task force looking into the cause of the Challenger accident. Before going to Princeton, Mr. Thompson spent 20 years as manager of the NASA/aerospace industry team that developed the main engine of the Space Shuttle, perhaps the most sophisticated machine ever built. He also served as Associate Director for Engineering in the Center's Science and Engineering Directorate, the organization responsible for developing many of the nation's space projects. Today, as Director of one of NASA's largest and most diversified centers, Mr. Thompson is responsible for many of the agency's top programs.

Under Mr. Thompson's leadership, the Marshall Center is responsible for a wide variety of NASA projects ranging from development of the Edwin P. Hubble Space Telescope and production of the propulsion elements of the Space Shuttle to management of Spacelab Earth-orbital missions and other payloads for the Space Shuttle. Also, the Marshall Center has been given a substantial role in the development of Space Station, a permanent manned facility proposed by President Reagan to be in orbit by the mid-1990s.

William Claiborne McCorkle, Jr.
USAMICOM/RDEC

Welcoming Speaker

As MICOM Technical Director, Dr. McCorkle serves as the senior technical advisor to the Commander on all research and development matters. As Director of the Research, Development and Engineering Center, he is responsible for providing major research, development, production, field engineering and software support to more than twenty MICOM project and product managed systems. In addition, he is responsible for planning and executing the Missile Command's programs in research, exploratory and advanced development of missiles and high energy lasers.

Dr. McCorkle came to the Missile Command in 1957 from a position at Tulane University and has since served in a number of increasingly responsible scientific and engineering positions, including an 18-month rotational assignment in the Department of Army Staff as Science Advisor to the Director of Weapons Systems. He has worked on missile-related research and development problems and projects associated with virtually every missile and rocket system under MICOM cognizance. His contributions include numerous papers and patents in guidance and control, such as the complete guidance system used in the LANCE missile, and major improvements to the HAWK missile system, including the most recent improvement permitting multiple simultaneous engagements. He has achieved national recognition for initiating and guiding the Center's highly successful pioneering work in fiber optic guidance links for missiles, providing a revolutionary new countermeasure-resistant capability for finding and engaging both rotary wing and armored targets out of the gunner's line of sight. Dr. McCorkle has long effectively championed the use of simulation techniques for missile design and analysis and initiated the effort that led to MICOM's Advanced Simulation Center, a major national facility and key to a number of successful missile development and improvement programs.

In November 1980, Dr. McCorkle was selected for the dual role of MICOM Technical Director and Director of the U.S. Army Missile Laboratory (now the Research, Development, and Engineering Center).

Dr. McCorkle holds a Ph.D. in physics from the University of Tennessee and a B.S. in physics from the University of Richmond, Virginia.

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NASA KEYNOTE

J. B. Odom
Associate Administrator for the Space Station
NASA HQ

James B. Odom
NASA HQ

Keynote Speaker

James B. Odom, who recently assumed the duties of Associate Administrator for the Space Station, worked at Marshall Space Flight Center for more than 30 years, serving as Director of the Science and Engineering Directorate from 1986 to 1988 and prior to that, was Manager of the Hubble Space Telescope Project.

At Marshall Space Flight Center, Mr. Odom has held many engineering and management positions. He was highly involved in the development of earth satellites and unmanned space probes before his assignment as Chief of the Engineering and Test Operation Branch for the Second Stage of the Saturn Vehicle. In 1972, he was appointed Manager of the External Tank Project in the Space Shuttle Project Office. He became Manager of the Hubble Space Telescope Office in 1983.

Mr. Odom graduated from Auburn University in 1955 with a BS in Mechanical Engineering. He has received numerous NASA awards including the NASA Exceptional Service Medal in 1973 for his contributions to the Saturn S-2 stages and the NASA Distinguished Service Medal in 1981 for his work in developing the Space Shuttle and its successful first orbital test flight. In 1985, Mr. Odom was awarded the Presidential Rank of Meritorious Executive in recognition of his contributions to both the External Tank and Space Telescope Projects.

ARMY KEYNOTE

J. D. Weisz, Director
Human Engineering Laboratories,
LABCOM

John D. Weisz
Human Engineering Laboratories
LABCOM

Army Keynote Speaker

Dr. Weisz joined the Human Engineering Laboratory (HEL), Aberdeen Proving Ground, Maryland in 1953 and was appointed Director of the Laboratory in 1957. The laboratory became the U.S. Army Human Engineering Laboratory, a separate activity reporting directly to the U.S. Army Materiel Development & Readiness Command (DARCOM) in Alexandria, Virginia.

The HEL has been designated as the Lead Laboratory for Human Factors Engineering Technology within Department of the Army and DARCOM Lead Agency for Robotics and Military Operations in Urban Terrain (MOUT). The primary mission of the HEL is to assure that Army materiel evolved conforms with the capabilities and limitations of the fully equipped soldier to operate and maintain the materiel in its operational environment consistent with tactical requirements and logistic capabilities. Dr. Weisz has been very active in the area of manpower resource integration efforts in Department of Defense (DoD) materiel development programs. He served on a special DoD study in 1967 and helped write the first Army Regulation (AR 602-1) on this subject. He also served as a member of the Army Research Council which reported directly to the Assistant Secretary of the Army for Research & Development.

Dr. Weisz has authored numerous technical reports and articles in technical journals in the fields of human factors engineering, psychosomatic medicine, retardation, and experimental physiology. Dr. Weisz is also a member of the National Research Council Vision Committee and the Acoustics Committee; Sigma XI, and has served as President of the Northern MD Retarded Association (NARC) and the Maryland Association for Retarded Citizens, Inc. (MARC).

Dr. Weisz also has received a number of awards, among them are the Junior Chamber of Commerce Outstanding Young Citizen; Outstanding Performance and Superior Performance; DA Certificate of Achievement; Department of the Army Decoration for Meritorious Civilian Service and the Department of Army Decoration for Exceptional Civilian Service; Award of Merit as employer of the year for employment of the Handicapped, State of Maryland; the DoD Distinguished Civilian Service Award and received the first Leslie Simon Award presented by ADPA.

Presented at the Conference on Space and Military
Applications of Automation and Robotics
21-22 June 1988 GACIAC PR 88-02

ARMY ROBOTICS PROGRAM EVOLUTION

6 June 1988

Dr. John D. Weisz
Director
U. S. Army Human Engineering Laboratory
Aberdeen Proving Ground, Maryland 21005-5001

ABSTRACT

This paper reviews the motivations for Army use of robotic systems and describes the emergence of an important initiative in the development and application of robotics technology for Army missions. Its principal focus is robotics for battlefield and support areas.

Our involvement at HEL in robotics began in late 1980. At that time, I attended a National Academy of Sciences review of robotics technology and its application to industry and government.

Even at this early date, it was evident that the Army could obtain enormous leverage from this technology and that, perhaps paradoxically to some, the development of effective soldier machine interfaces to these systems would be critical.

Paradoxically, because to some the word "robotics" implies no human interface; in actuality, a critical requirement in the evolution of machines with the ability to perform a diverse array of sophisticated functions, i.e., true robots, is a requirement for new methods of human interface. This requirement exists because the existence of an effective human interface:

- permits earlier fielding of robotic systems thru allocation to the human of those functions not amenable to fully automated function;
- generally permits a less operationally constrained use of the robotic capability;
- is crucial for maintenance (smart maintenance for the smart machines or there may be no net gain);
- is critical to the acceptance of a technology which is in its infancy, and which will frequently be associated with application of deadly force.

It is crucial to the realization of the true military significance of robotics that a variety of interface approaches be developed and that full-time human control in a telepresence mode not be the sole mode of interface.

This variety of interfaces is necessary in order to realize major advantages from the combat application of robotic systems (as opposed to subsystems such as tank autoloaders). These advantages accrue from opportunities for:

•remote operation of the system as a means of improving the soldiers survivability;

•proliferation of a group of expendable systems. Overlay on these conditions a declining manpower pool, and you have a situation in which dedicated broad band teleoperation of each system is neither desirable nor practical. Development of a class of interfaces in which significant autonomy on board the machine enables low data rate communications between soldier and machine entails an entirely new class of interface issues, e.g., what is the most critical info to display from both temporal and spatial sampling standpoints? The low data rate communication capability provides opportunities to utilize robust low probability of intercept RF communication links which do not saturate the portions of the spectrum which support non-line-of-sight communication. A three-order of magnitude reduction in communication data rates is neccessary to move from the data rates typically used for teleoperation to those supported by tactical communication systems such as SINCGARS.

Another conclusion I reached as a result of the early 1980 National Academy meeting was that there was an experience base in NASA, the DOE labs, the National Bureau of Standards, and in industry that was directly applicable to the Army's nascent interests in robotics. We have worked hard as a community to leverage these groups.

(VG #1: EARLY AND CONTINUING SOURCES OF LEVERAGE)

In 1981, I requested DARCOM Headquarters to assign HEL a lead role in robotics technology. Our laboratory has had a long and very positive relationship with the Army's user communitity in programs such as the Human Engineering Laboratory Battallion Artillery Test series of experiments at Ft. Sill. Early in the robotics program, I saw a need to develop a similar close tie with the user community. It was and is especially important in the application of a virtually unprecedented technology such as robotics to generate a close rapport with users of the technology. Thus early in 1981, I solicited GEN Don Starry, then CG TRADOC, to identify a lead agent for robotics within the Training and Doctrine Command. GEN Starry identified the Soldier Support Center (MG French commanding) as the lead, and we initiated a series of joint DARCOM/TRADOC Steering Group meetings to perform technology assessments for robotics applications identified as having strong user interest. This early working group met in 1982-1983 and helped precipitate a

TRADOC initiative to form a General Officer Steering Committee for Artificial Intelligence and Robotics.

(VG #2: MAJOR EVENTS IN PROGRAM EVOLUTION)

Other significant events occurring during this period included studies performed by the Army Science Board, a major contract study performed by SRI for the Engineer Topographic Laboratory, and some early demos of the capabilities of robotics for mineclearing and ammunition handling

(VG #3: ROBAT)

The mineclearing activities were led by now retired Major General Bob Sunnel, and the ammunition handling experiments were conducted by HEL and Tooele Army

(VG #4: RALS PROJECT.)

Depot, with assistance from Unimation Inc.

The studies identified a myriad (some 75) TRADOC interests in the application of robotics technology. Thru this study and others by the NRC and ASB, consistent factors emerged motivating Army application of the technology. Indeed, the next major 'udy effort by the National Reserach Council captured these themes in its title "Applic- ' n of Artifical Intelligence and Robotics to Reduce Risk and Improve Effectiveness." Reference to one of our current briefing charts reflects this emphasis.

(VG #5: ROBOTICS EXPLOITATION)

The critical requirement at this point was to select a manageable number of demonstration projects and to put in place plans and funding to develop, integrate and evaluate the utility of robotics technology thru demonstration projects and hands-on troop experience.

The opportunity to perform this function came when LTG Bob Moore, then Deputy Commanding General for Research Development and Acquisition, AMC and a former MICOM commander tasked us to draft a robotics investment strategy for the Army.

I'll review the strategy we proposed which LTG Moore, Gen Thompson at that time our CG, and Gen Richardson, then TRADOC CG approved.

As indicated above, there was no shortage of good ideas for the application of robotics technology. If anything, there was and is a danger that pursuit of too many of these ideas will lead to such fractionation of available resources that robotics will experience a setback. Paramount in LTG Moore's mind was the establishment of a set of protected programs which could serve as a focal point for the total program. We, jointly with the recently formed Arroyo Center component of the Rand Corporation, decided at that time to make that focus telerobotic vehicles and telerobotic manipulators for logistics operations. The rationale for this decision was that focus on these two groups of programs would either utilize or lead to advancements in virtually every segment of the robotics tech base in areas critical to the support of a large number of robotics projects in the future.

This lead then to the selection of three programs within the two areas of telerobotic vehicles and manipulators:

TELEROBOTIC VEHICLES
TMAP and the Robotic Combat Vehicle Program

TELEROBOTIC MANIPULATORS
Field Material Handling Robot Program

(VG #6: PROGRAM EVOLUTION)

We proposed an initiative titled TMAP or Teleoperated Mobile Anti-Armor Platform as a near term, multi-purpose platform which would initially be configured with light anti-armor weapons. This program was proposed building on the BRL/ Grumman Ranger experience to explore the low cost, low signature, expendable end of the telerobotic vehicle spectrum. The intent was to couple the operator to the TMAP thru a wide band fiber optic link. The teleoperated mode of operation was a key aspect of this system in that this was a crucial safety related issue for a system configured with weapons. We recommended that MICOM be given the lead for the TMAP portion of the overall robotics program in recognition of their experience base with missile weapon systems, associated fire control and fiber optic data links.

(VG #7: TMP)

We are presently faced this year with some congressional language which required us to a eliminate a weapon as part of the TMAP. AMC and TRADOC HQ are due to brief the staffer who instigated this action on the Army's interests in robotics and robotic weapon systems in the near future.

With the exception of the weapon issue which has caused the deletion of the weapon and a retitling of the program to Teleoperated Mobile Platform (TMP), the TMP program is on track thru contracts managed by Sandia National Labs for MICOM. Two TMP demonstrators are under development and will be provided in the fall of this year. Sandia developed and demonstrated a small variant of the TMAP concept called Fireant. It represented the ultimate in expendable systems.

(VG #8: Fireant)

The Fireant platform is destroyed in the process of shooting a large explosive-formed penetrator warhead. The evaluation thru troop use of these platforms for roles in EOD, battle damage assessment, forward observation, designation, etc. will be a major milestone for the Army's robotics program. As a result of a 1986 Concept Evaluation Program test at Ft. Benning, considerable attention has been focussed on the user interface to TMP, particularly as regards low cost but effective land navigation. Another key issue in the TMP program is the capability to move beyond one-on-one teleoperation to some aspects of one-on-many soldier control of multiple vehicles thru target cueing capability.

While TMP represents the low cost, near term end of the telerobotics spectrum, the Robotic Combat Vehicle (RCV) effort focusses on longer term tech base developments, permitting multiple vehicle control, in a mobility and mission package sense, untethered operation and higher levels of mission autonomy. The two principal elements of the RCV program are the Robotic Command Center and Tech Base Enhanced Autonomous Machines (TEAM) programs.

(VG #9: RCV TEAM System Features)

The TEAM program is one of two major LABCOM initiatives comprising a cooperative laboratory program. This effort was motivated by a LABCOM HQ desire to foster programs which would focus the tech base efforts of multiple labs on areas of future materiel development. Key thrusts within the TEAM program include command and control of two robotic vehicles configured to permit realistic operational missions for robotics, mobility and mission package control thru tactical radio communication links, autonomous mobility over previously traversed routes, mission packages permitting autonomous target acquisition, and in the future autonomous target engagement when the aforementioned certain congressional prohibitions are lifted regarding the use of weapons on robotic combat vehicles. I touched on the data rate issue earlier in the briefing. The following slide is germane to this issue.

(VG #10: COMPARISON OF DATA RATES)

HEL has a lead role for the TEAM within LABCOM. As you can see, we have a large number of participants in this effort reflecting the intention of utilizing the diverse contributors I spoke of earlier in the briefing.

(VG #11: TEAM PARTICIPANTS)

The Robotic Command Center (RCC) effort is a TACOM initiative under the Robotic Combat Vehicle (RCV) program. This effort concentrates on integration of a robotic vehicle command and control capability into a volume compatible with transport on an armored vehicle, specifially a variant of the M109 chassis.

(VG #12: ROBOTIC COMMAND CENTER)

The RCC houses three operator workstations, one for a commander and two vehicle driver workstations.

(VG #13: RCC DRIVER STATION)

It is configured to enable driving of robotic vehicles with substantial levels of mobility related autonomy for functions such as road following. The RCC will be Computer Aided Remote Driving (CARD) compatible. CARD, developed by the Jet Propulsion Laboratory from techniques originally developed for Mars rover exploration missions, enables the driver to visually observe and designate intermediate trajectory points (via points) for the vehicle. The vehicle can identify and traverse a straight line path thru a series of these points autonomously, assuming no unobserved or new obstacles appear. After path planning, this capability will, over some types of terrain, provide a single operator the ability to control multiple, simultaneously maneuvering vehicles. In addition to these functions, RCC will incorporate sophisticated mission planning and route selection software integrated with terrain database analysis capabilities. FMC, San Jose, is the prime contractor for the RCC effort.

A major issue in the RCV program is the development and implementation of a standard set of communication and interface specifications which will enable RCC and TEAM, as well as other robotic vehicles, to be operated without requirements for multiple command and control workstations.

(VG #14: SOLDIER CARRYING 8" PROJO IN THE MUD)

A second major area of importance for the application of robotics for the Army is that of material handling functions. There are an enormous number of labor intense, in some cases hazardous, manipulative functions embedded in combat, combat support and combat service support functions. These include heavy lift for a variety of logistics and engineering functions as well as dexterous operations performed at substantial risk to members of the Explosive Ordnance Disposal community. A 1983 National Academy of Sciences review of the application of robotics to the Army recognized the many application potentials for robotics in the field environment by stating that robotic material handling syst s would become as ubiquitous as the jeep in the future battlefield. In recognition of this and the different issues tech base required to utilize robotics in the field environment as opposed to the factory, an early decision was made to focus a major element of the Army's robotics technology investment on manipulator systems.

The Field Material Handling Robotic Technology (FMRT) project is the largest such project. It is developing and integrating a wide variety of technologies such as servo control, robotic sensing, safety, advanced computing architectures, manipulator design and packaging into a robotic manipulator testbed of unprecedented capability.

(VG #15: FMRT SLIDE)

This system will be capable of autonomously acquiring and transferring at high rates a variety of palletized workpieces. Both the FMRT and TEAM projects are utilizing the National Bureau of Standards' developed Real-Time Control System (RCS). RCS is a well-structured architecture whose hierarchical state table basis facilitates easy user interaction at any of its levels. Use of the RCS leverages over $20 million dollars of Navy investment. The RCS architecture has been adopted by NASA as a standard reference model. HEL, for LABCOM, Tooele Army Depot, the National Bureau of Standards, Belvoir RD&E Center, and Martin Marietta, Baltimore (the FMRT prime contractor) all have participated roles in the development of FMRT.

The FMRT testbed is specifically designed to enable the Army to evaluate efficiency increases realizable thru the development of logistics workcells. Technology products from the FMRT program will be applicable to a wide range of field oriented and industrial robotics development efforts. One example of this is the sensor-equipped end effector,

(VG #16: FMR-X TESTBED END EFFECTOR)

This unit will be adapted to new forklifts permitting autonomous pallet acquisition

(VG #17: UNIVERSAL SELF DEPLOYABLE CARGO HANDLER)

One can easily imagine the use of this technology with industrial equipment in a loading dock upload or download scenario. In this sense, the Army program not only draws from, but contributes to, U. S. industrial competitiveness.

FMRT testbed is scheduled for FY89 completion.

DARPA has initiated a program titled "Advanced Robot Manipulator System (ARMS)" which performs much the same technology development and integration function for dual-arm dexterous manipulation that the FMRT program is performing in the heavy lift domain.

(VG #18: ARMS

This presentation is by no means exhaustive of the robotics programs being pursued within the Army or for that matter other worthy programs in the other services. It has described a group of projects that the Army has singled out for emphasis and the motivations for their selection. With the development of TMP, we will have the opportunity to place some of the earliest products of this program into the field for rigorous troop testing. Machines such as the FMRT and RCV's represent the next wave of opportunities in which truly intelligent machines capable of a wide variety of independent, sophisticated functions will be available for evaluation with troops in the field environment.

In conclusion, we are rapidly nearing the time when it will be possible to test many of the assertions made regarding the application of robotics to key Army missions. If one stands back and looks at these concept developments from a broader point of view it is clear that we are preparing for a series of experiences with an embryonic technology which will have a major impact on our defense in the aggregate, and in a very direct way, for the soldier of the future.

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PLENARY PRESENTATION

Steve Bartholet
Odetics, Inc.

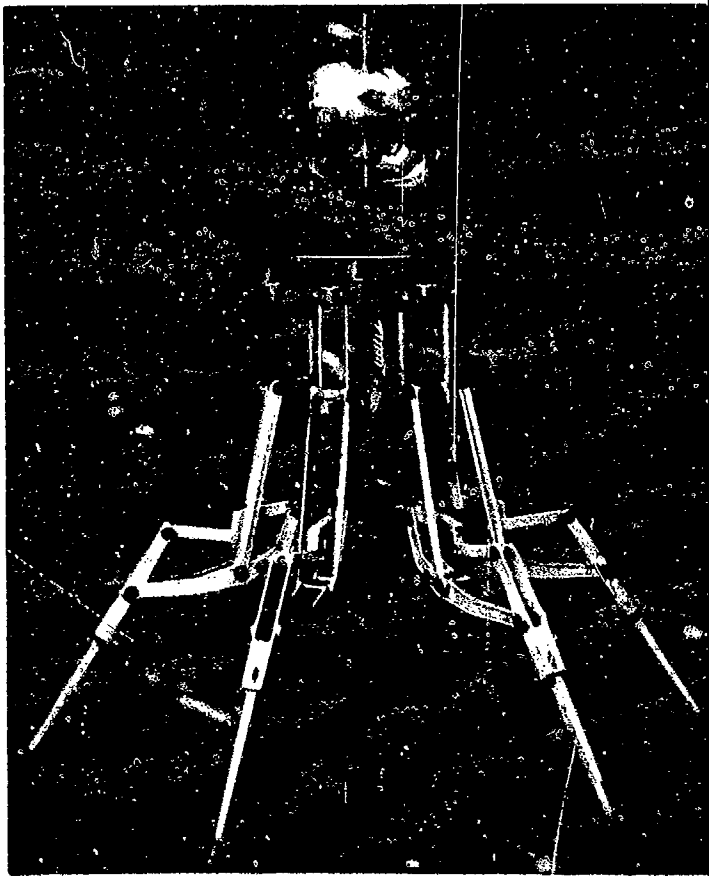
Steve Bartholet
Odetics, Inc.

Plenary Speaker

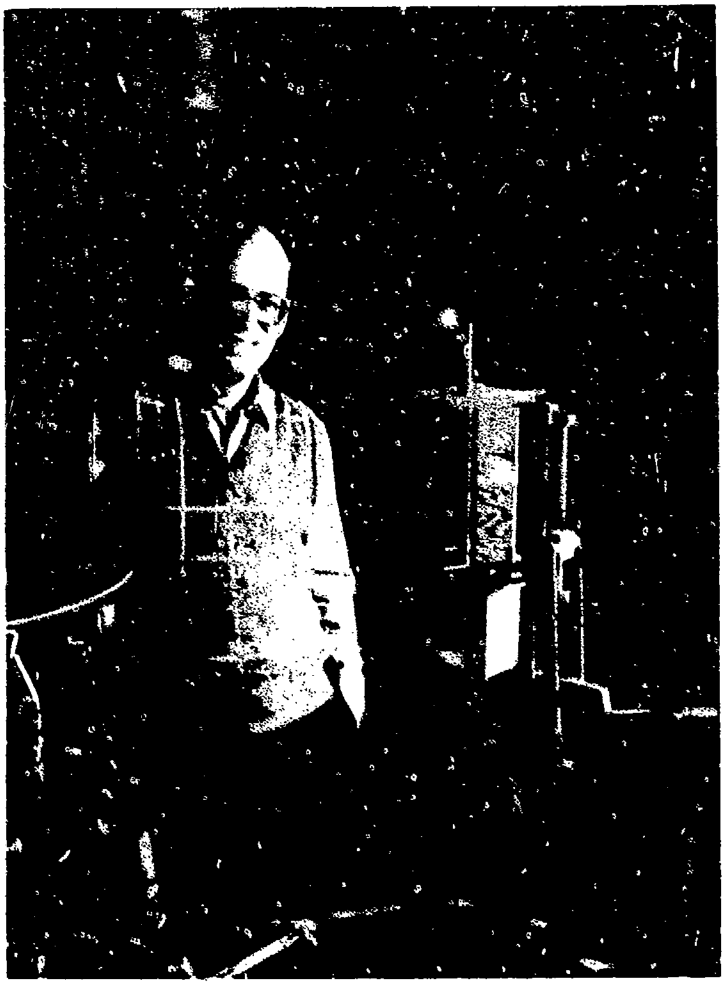
Steve Bartholet conceived and managed the construction of ODEX I, the six-legged walking robotic demonstrator for which he and Odetics, Inc. hold patents for the leg mechanisms. The Odex I was built as a technology demonstrator and resource base for future intelligent machine system developments. Each of the six legs has three degrees of freedom. The total of 18 d.o.f. must be controlled in real-time through algorithms for the 6 legs, which share overlapping work spaces.

At "Robots 11" in April 1987, he was presented the First Annual Jean Vertut Award for Excellence from Robotics International.

Force-component isolation designs were invented by Mr. Bartholet for the ODEX I legs. Each of the six legs weighs 50 pounds, including motors, gears and all sections. The lift capability of each leg is 45 pounds in any position. The computing power of the ODEX greatly simplifies the man-machine interfaces. The teleoperator deals only with high-level commands for mode of operation, selection of parameter boundaries, and driving of the body of the ODEX through a rate-control joystick. The teleoperator can similarly take control of any leg and operate it as an arm. The legs are under state-of-the-art closed-loop, continuous path trajectory management. Yet, the new advances in embedded computer control represented by the ODEX result in smooth, rapid, and continuous motion.



THE FIRST FUNCTIONOID ODEX I



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Session II Program A

IVA Robotics

Chair: Pam Nelson, NASA/MSFC

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Keynote Speaker: W. B. Chubb, Director
Information and Electronic Systems Laboratory
MSFC

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21-22 June 1988 GACIAC PR 88-02

DUAL-ARM ROBOT FOR TELEROBOTIC IVA OPERATIONS ON THE SPACE STATION

21-22 June, 1988

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ABSTRACT

Sometime near the middle of the next decade, the United States Space Station will achieve initial occupancy. The crew of the Space Station (SS) will have to perform three major groups of tasks. These are normal station-keeping tasks, assistance in completion of SS construction and scientific experiments. Obviously, such a range of tasks requires great flexibility and adaptability. Such capability is only achievable by the use of highly trained crews. However, each succeeding estimate of initial SS crew size seems to become smaller. Currently, crew sizes of six to eight are being discussed.

The SS crew will have to perform tasks in two environments: EVA (Extra-Vehicular Activities) and IVA (Intra-Vehicular Activities). The IVA tasks are assumed to include the most intricate operations because they will be involved in most of the scientific activity.

To extend the capability of the limited initial SS crew, it is planned to use teleoperated robots with dextrous manipulators. These robots must perform tasks devised such that the human crew can replace the robot in case of equipment failure. If large scale augmentation of the capability of the SS crew is to be achieved with robots, some or most of these robots must be of the two-armed type.

Kader Robotics has designed a unique dual-arm robot that is particularly well-suited for use in the confined spaces of the Space Station. This paper describes the characteristics of this robot.

1.0 INTRODUCTION

The number of industrial robots in use throughout the world totals in the tens of thousands. It is very safe to state that the great majority of these robots are of the single-arm type. There is a very good reason for this fact. These industrial robots perform repetitive, pre-programmed tasks. Usually, the workpiece is positioned and held by other devices or fixtures. The robot need only perform a simple function such as bringing a welding electrode to a given location,holding it briefly in place and then retracting it. It is believed that there will be rather little of such work requirements inside the Space Station. Instead, there will be a need to assemble and disassemble machinery and scientific equipment and perform delicate, precise tasks associated with microgravity and other experiments. In other words, much of the work will be the kind performed by a skilled workman using both hands.

The SS crew will need to be aided by two armed robots. Also, these robots will need to be accurate and dextrous. There have been earth-based needs for such robots in the past and much can be learned from their development.

2.0 TWO-ARMED ROBOTS ON EARTH

Two areas of early two-armed robot development are within the nuclear industry and on submersible work vehicles [1,2]. In the case of the nuclear industry, considerations of radiation hazards required that numerous intricate tasks be performed without the direct use of human hands. Initially, this was accomplished through use of the un-powered (human-powered) master-slave manipulator system. In this system, a near-remote pair of dextrous manipulators is operated through mechanical linkages by an operator whose own hands and forearms are encased in a similar set of "master" manipulators. This system was successful for light tasks performed only a few feet away from the operator. For heavier, more remote tasks, a power-boosted system was developed.[3]

In undersea work, it is often advisable to perform complex and unstructered tasks with a subersible work vehicle that is equipped with two or more manipulator arms. A third or "grappler" arm may be used to hold firmly to the workpiece to deal with undersea currents. Thus the two dextrous arms will be free for work functions. Underwater manipulator arms operate with certain disadvantages. Water pressure on seals and joints would make manually operated arms hard to manipulate. Thus remotely powered arms are almost mandatory. However, the worksite can be directly viewed from a close distance, making control somewhat easier.

3.0 SPECIAL DEMANDS OF THE SPACE STATION

Some aspects of the Space Station (SS) have been mentioned earlier herein. There is a need to augment and amplify the work capabilities of a modest SS crew for tasks both inside and outside of the habitat. However, it is not believed practical to achieve these goals through use of a fully autonomous two-armed robot. Such a robot would likely need to have a certain amount of mobility such as along a rail, within a given work area. It is quite possible that an SS crew member would need to be within the same module as the robot. The consequences of the malfunction of a fast, powerful robot under these circumstances may easily be imagined. Thus the consensus of NASA planners is that the first generation of space robots will be teleoperated types.

By definition, a teleoperated system involves a human in the control loop. As has just been stated herein, this is a function of the need to avoid the hazards of a fully autonomous mobile robot. The question may arise "how can such an arrangement of one crew member per robot <u>increase</u> the capability of the SS crew to perform tasks?" There are several answers to this question. For example, the Space Station will feature an unpressurized module to receive and store propellants and other hazardous materials. If this module was directly serviced by a space-suited crew member, the work would be slow and cumbersome as well as hazardous. A teleoperated robot would be ideal for such work.

Regarding crew amplification by use of teleoperated robots, this can be obtained by the addition of intelligence to the teleoperator control system. In this manner, a library of instructions for the performance of common tasks or task elements can be developed. The operator can select tooling and guide the robot manipulators to the precise worksite. Then the robot can be commanded to perform a pre-programmed task while the operator does something else, such as directing a second robot.

The ultimate of adding intelligence to teleoperated robots will occur when artificial intelligence (expert systems) are incorporated into the control loop.[4] With this capability, the robot can locate the worksite and perform the classic"peg in hole" type of operation.

It should be obvious that advanced teleoperated robots will be costly items. However, recent estimates of the cost of SS crew work time are that it will cost at least $20,000/hour. Thus a generous "robot budget" is indicated. Another factor here is the decision to perform a variety of microgravity experiments aboard the Space Station. This work will probably include limited manufacture of products. It is now known that some of these operations will require microgravity acceleration environments of 10^{-6} G or less. It is impossible for a human to work in close proximity of such low acceleration environments without disturbing them. Thus use of a specialized robot is mandated here.

4.0 THE KADER DUAL-ARM ROBOT

The Kader Robotics Corporation (KRC) has been a supplier of custom robotics sytems to NASA for several years. When the need for a two-armed space robot began to be defined, KRC designers considered the existing two-armed robot designs such as those in the nuclear and underwater service industries described earlier herein. If a single robot is to have two independent arms, they could be mirror images of each other. as with the human body. Alternatively, the two arms could be identical, which simplifies both design and the stocking of spare parts. The KRC "dual-arm" robot concept uses neither of these traditional approaches.

The KRC dual-arm robot employs arms of unequal length wherein the waste joints rotate about a common axis (Figure 1). This approach reduces a problem common to two-armed robots, namely interence between the movement of the arms. Another advantage of unequal length arms is that the shorter arm (secondary arm) can pass through the longer one (primary arm), thus allowing the secondary arm to work above or below the primary one. This capability is better seen in Figure 2. The U-shaped upper segment of the primary arm is open to passage by the secondary arm, which can be shortened by employment of a telescoping forearm section.

4.1 METHODOLOGY OF DESIGN

A major consideration in the design of the KRC dual-arm robot was the anticipated end use in a space vehicle or orbiting station. It was understood that the final hardware would have to be lightweight, reliable, easy to service and repair and also highly versatile, given the wide variety of anticipated tasks, both planned and unplanned.

Early attempts to formulate dual arm systems posed many problems, among which collision avoidance and computational linearity were the most severe. Comparison and analysis of the arm kinematics in real time, plus inverse kinematics and reaction dynamics posed massive problems. Some analytical projection of the leading edge of the end effectors was predictable. However, when the end effectors were made interchangable and the workpiece variables were introduced, it became necessary to utilize additional sensory elements and to reduce the angular mechanics of the manipulators.

One solution contributing toward reduced complexity in control algorithms and in computational linearity was the decision to eliminate the traditional elbow joint in the arm design. This is made possible by substituting linear extension of the forearm. This design resulted in the elimination of jerking during arm movement, a problem common to coventional "elbowed" manipulator arms.

The decision to have both arms rotate about a common base has advantages beyond collision avoidance. For example, this concept reduces the amount of backlash and deflection as compared to dual arms that do not have a common base. Other considerations to this line of thought were to preload all joints and to design structural members for minimal deflection under load. This general approach results in improved accuracy and repeatability of movement, which is very important when performing dextrous tasks in a manner that mimics human capability.

4.2 VERIFICATION BY SIMULATION

The dual-arm manipulator concept-mechanics, by their nature add some complexity to the control logic. Individual manipulator arm control can no longer be addressed as a simple single kinematic envelope. Relationships of one manipulator to the other, and, in the case of the KRC dual-arm robot, passage of the secondary arm, become control conderations. Kader Robotics Corporation realized that the latest analytical tools should be employed to verify the operating concepts and control mathematics for the dual-arm robot. Therefore, KRC funded a graduate student (Hsueh Min Chang) at the University of Alabama in Huntsville (UAH) to derive forward and backward kinetics equations for the advanced dual-arm manipulator (ADAM) and demonstrate the operation of the robot on a color video screen.

The simulation of ADAM motion was developed as a C language program which was based on the method of coordinate transformation for describing robot kinematics in the IRIS 3270 Graphics System. IRIS is a registered trademark of Silicon Graphics Company, Mountain View, California 94034. Using this equipment, visual aids were developed that permitted viewing the motion of the robot from different positions and angles. These include views from the top, bottom, front, back, right and left sides, together with zoom capability. The color video display of the motion of the ADAM arms served to verify the control equations as well as to demonstrate the unique features of this robot, including the ability to pass one arm through the other. With further development, this simulation could serve as a training aid for future operators of KRC dual-arm robots.

4.3 THE ASTROBOT CONCEPT

This paper deals primarily with the use of the KRC dual-arm robot in a Space Station IVA environment. This is not to say that the concept would not be equally desirable to perform a wide range of anticipated SS tasks within EVA. In fact, KRC has designed a free-flying teleoperated multi-arm robotic vehicle to service the exterior of the Space Station. Such a vehicle is shown in Figure 3. It could retrieve satellites as well as perform a variety of maintenance and repair tasks. As such, it could supplement fixed base SS EVA telerobots such as the Canadian Mobile Servicing System (CMSS) or the Human Occupied Space Teleoperator (HOST). 5

5.0 CONCLUSIONS

The KRC dual-arm robot concept offers the following advantages for use in Space Station IVA operations:

- o Compactness
- o Versatility
- o Simplified Control
- o Accuracy and Repeatability

This basic robot geometry can be used a major building block in an evolutionary space teleoperator system that will initially require considerable human supervision but can later be upgraded by the addition of artificial intelligence to greatly increase the work output of Space Station crews. In this way, the huge financial investment in the Space Station can be well-utilized without the high cost and risk associated with the maintenance of large SS crews.

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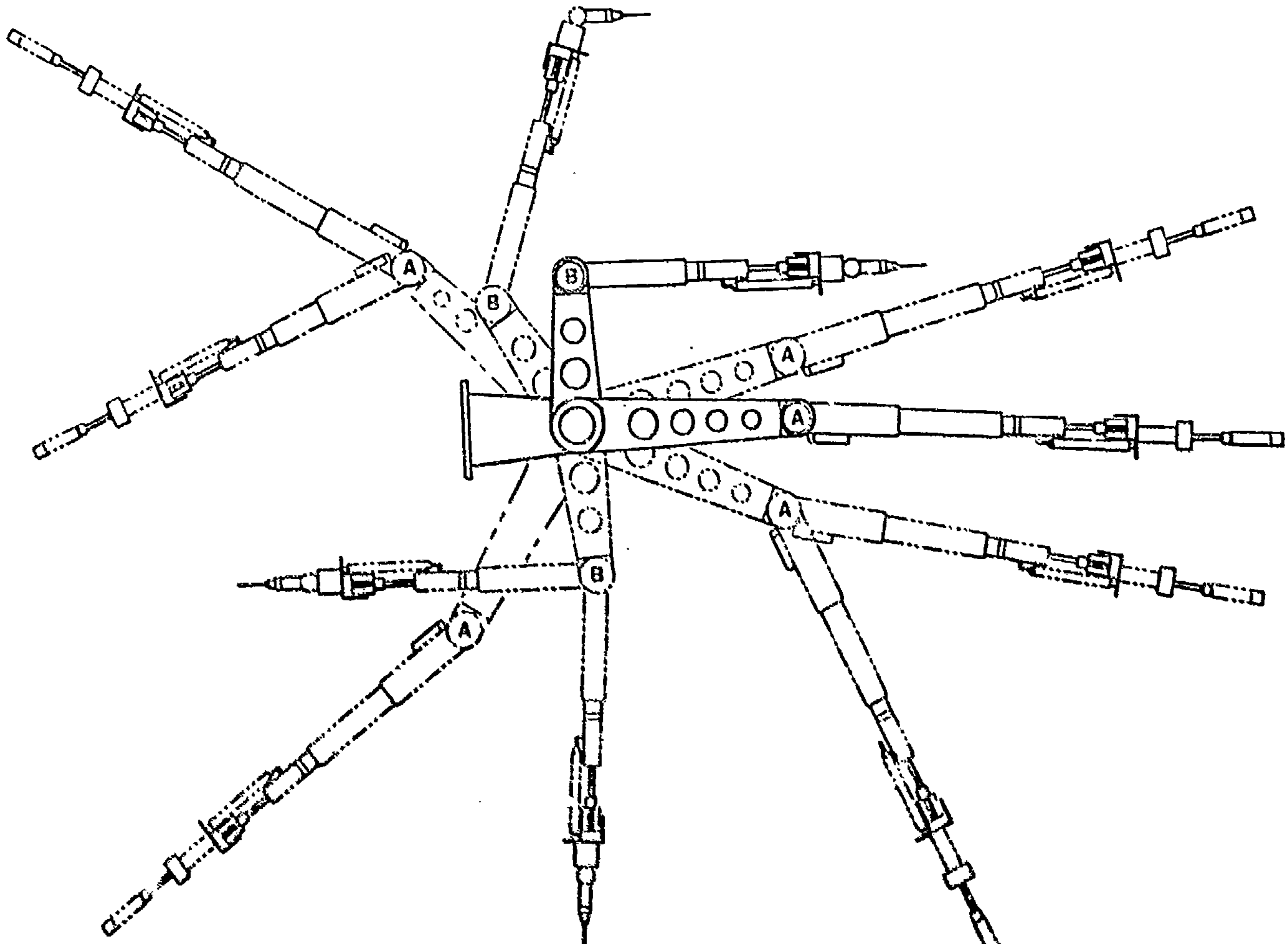

Figure 1 DUAL-ARM ROBOT

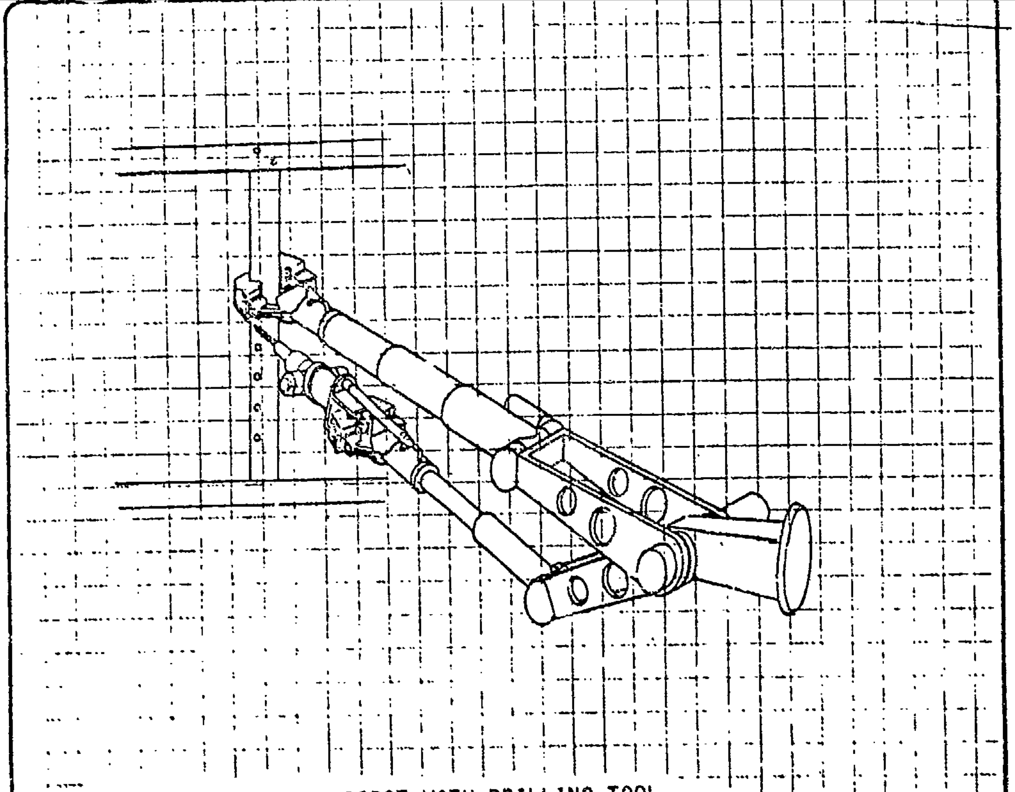

Figure 2 DUAL-ARM ROBOT WITH DRILLING TOOL

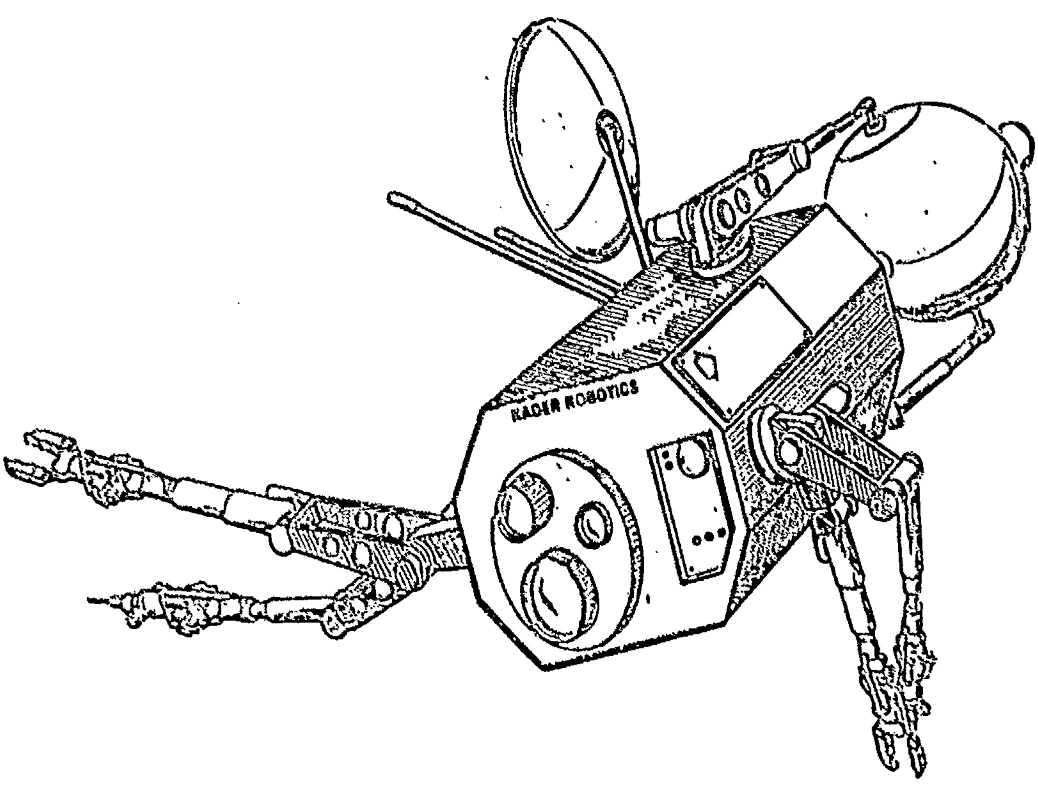

Figure 3 KADER ASTROBOT FREE-FLYING ROBOT

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THE IMPACT OF AN IVA ROBOT ON THE SPACE STATION MICROGRAVITY ENVIRONMENT

28 April 1988

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ABSTRACT

In order to maintain a microgravity environment during Space Station operations, it will be necessary to minimize reaction forces. These mechanical forces will typically occur during reboost, docking, equipment operation, Intravehicular Activities (IVA) robot operation, or crew activity. This paper focuses on those disturbances created by an IVA robot and its impact on the Space Station microgravity environment. The robot dynamic analysis that was used to generate the forcing function as the input into a finite element model of the U. S. Laboratory will be shown. Acceleration levels were determined through analysis and have shown that a robotic system can sustain reaction forces into the station below 10^{-4} g. A comparison between IVA robot effects and crew motion effects on the low-g environment is also described. It is concluded that robot trajectory shaping and motor accelerations feedback can minimize reaction forces.

1.0 INTRODUCTION

The development of a microgravity materials processing capability within the Space Station United States Laboratory (USL) will provide the United States and its partners the opportunity to perform significant research leading to the commercialization of space processing. The major resource in space being the microgravity environment, establishing and maintaining a low gravity is a major requirement and dictates the placement of mechanical equipment and the operational procedures in order to minimize disturbances to such a facility. In order to manage and sustain such an environment, a highly automated and tightly timelined facility would be a viable solution. Also, because a majority of the material processing experiments require crew interaction, some form of automation and robotics will have to be incorporated into the design of the space station to achieve this requirement.

Teledyne Brown Engineering (TBE) is conducting a User Needs, Benefit, and Integration Study under contract to the NASA Lewis Research Center. A part of this effort was to quantify the effects of microgravity manipulation in order to characterize the attributes of the robot manipulator. Initially, an assessment of Space Station user's automation and robotics needs was made in order to identify user sensitivity to g-level and maximum robot disturbance to the Space Station microgravity environment. Ground rules and assumptions were developed in order to set the ground work for the analysis and to have traceability. A kinematic and dynamic model of a typical manipulator was then developed in order to obtain a forcing function to be used as input to a Space Station module NASTRAN model. The NASTRAN model was based on a Space Station phase 1 configuration. Two load cases were examined and the results presented in graphical form.

2.0 IDENTIFICATION OF WORST CASE ROBOTIC MANIPULATION

Based on a survey of Space Station users' experiment operations and an assessment of the level of robot manipulation (References 1 and 2), TBE identified two experiments that are feasible candidates for robotic manipulation and represent two extremes of disturbance.

Protein Crystal Growth was identified as a specimen handling experiment that required less than 100 micro-g acceleration ($<10^{-4}$ g). This crystal growing process produces a sample that must be moved at very low accelerations. A robotic system would play an important role in transferring the sample, which is grown in a liquid, from the growth chamber to a characterization facility without submitting the crystal to hydrodynamic forces that could destroy the fragile structure.

The Large Bridgman Furnace (LBF) was identified as the specimen handling experiment that would cause the greatest disturbance to the Space Station microgravity environment during sample changeout. A Large Bridgman experiment weighing approximately 1800 kg must be translated for sample removal. There is no low acceleration requirements for this canister; however, if a robot system were to move and/or manipulate this hardware, the potential for large reaction forces into the station could effect the quiescent environment needed by the microgravity experiments.

The Large Bridgeman Furnace Experiment as a worst case specimen handling experiment was chosen to be analyzed in further detail.

3.0 GROUND RULES AND ASSUMPTIONS

The robot arm kinematic model was derived using inverse kinematics (Reference 3) and assumed that the three wrist axes [pitch ($\emptyset_4$), roll($\emptyset_5$), and yaw($\emptyset_6$)] would be stationary during LBF manipulation.

The robot arm dynamic model was derived using Lagrangian mechanics and was based on published information on dynamics of a PUMA manipulator (References 4 and 5). Gravity load terms were neglected due to operation in space and ignored inertia coupling because of the assumption that the response time of the joint servos decreases monotonically with increasing joint number. Because the manipulator will operate at low speeds for safety reasons, centripetal and coriolis forces were also neglected.

Masses and dimensions of the Space Station were obtained from the Space Station Pressurized Volume Utilization Study (SSPVU) (Reference 6). Also a detailed finite element model of the common U.S. module was used to derive the physical properties of the pressurized modules. This detailed module model was fixed at one of its berthing mechanisms while unit axial, lateral, and torsional loads were applied at the free end. The resulting displacements provided beam equivalent component stiffness. These values were then further factored by the module length and material elastic modules to provide the equivalent cross sectional area, moments of inertia, and torsional constants. All of the pressurized elements except the nodes are assumed similar in geometry and material composition and are, therefore, modeled as NASTRAN BAR elements that use the equivalent element properties. All pressurized element masses are assumed to be evenly distributed along their respective longitudinal axes. Endcone stiffness characteristics are covered by varying the berthing mechanism stiffness.

While two basic types of mechanism (rigid and flexible) are possible, it was assumed that "flexible" mechanisms would be present for buildup/alignment purposes only. Thus, for this study, it was assumed that the berthing mechanisms were "rigid."

The nodes are modeled differently from the other pressurized elements. The radial berthing mechanisms on the nodes stiffens the node in the radial direction. These nodes are therefore modeled as frames with a BAR element running along its longitudinal axis and perpendicular BAR elements extending from the node center to each radial port. The main longitudinal beam elements are equivalent to those in the modules, while the radial port beam elements are assumed to be twice as stiff in all directions.

To correlate systematically the effects of Station configuration a. l robot orientation with microgravity disturbances inside the USL, the two load cases used the main truss and interface truss models.

The Station configuration consists of the main truss, interface truss, and the manned core arranged as shown in Figure 1. For the robot load cases examined, the robot was located at grid points 126, 100, and 588.

Several factors influence the response of an experiment inside the USL resulting from IVA robot activity. These factors include 1) Station mass, 2) Station center of gravity, 3) distance of disturbance to center of gravity, 4) distance of experiment to center of gravity, 5) Station mass moments of inertia, 6) disturbance frequency, 7) local isolation, 8) structural damping, and 9) berthing mechanism stiffness. The first six factors are incorporated in the models. The effects of local isolation, either at the disturbance or at the experiment, is not quantified in this study. A proper active isolation system (with feed-back control logic) would, however, tend to diminish the effects reported in this study.

The inability to assign values to berthing mechanism stiffness or the structural damping factor with an acceptable degree of probability required the analysis to include a parameterization of these variables.

4.0 KINEMATIC ANALYSIS

In developing the equation of motion for the PUMA robot arm, the first step was to set up the appropriate coordinate system at each joint and at the base. In Figure 2 the PUMA arm is shown with coordinate frames assigned to the links. The parameters are shown in Table 1.

The A matrices for the PUMA arm are:

$$A_1 = \begin{bmatrix} C_1 & 0 & -S_1 & 0 \\ S_1 & 0 & C_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

$$A_2 = \begin{bmatrix} C_2 & -S_2 & 0 & a_2C_2 \\ S_2 & C_2 & 0 & a_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

$$A_3 = \begin{bmatrix} C_3 & 0 & S_3 & a_3C_3 \\ S_3 & 0 & -C_3 & a_3S_3 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

$$A_4 = \begin{bmatrix} C_4 & 0 & -S_4 & 0 \\ S_4 & 0 & C_4 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (4)$$

$$A_5 = \begin{bmatrix} C_5 & 0 & S_5 & 0 \\ S_5 & 0 & -C_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (5)$$

$$A_6 = \begin{bmatrix} C_6 & -S_6 & 0 & 0 \\ S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6)$$

where S_t refers to $\sin(\emptyset_t)$ and C_t refers to $\cos(\emptyset_t)$.

In order to control the manipulator, we are interested in the reverse problem, that is, given the x, y, and z coordinates of the end effector, what are the corresponding joint coordinates?

We may first obtain T_6 from the traditional approach to solve the matrix equation:

$$T_6 = A_1 * A_2 * A_3 * A_4 * A_5 * A_6 \qquad (7)$$

The inverse kinematic relations can then be derived for each joint angle. The first joint angle is obtained by matrix equality for the following equation:

$$A_1^{-1} * T_6 = U_2 = A_2 * A_3 * A_4 * A_5 * A_6 \qquad (8)$$

The value for $\emptyset_1$ can be obtained by equating the 3,4 elements from (8) resulting in

$$\emptyset_1 = \tan^{-1}(p_y/p_x) - \tan^{-1}(d_3/(r^2 - d_3^2)^{1/2}) \qquad (9)$$

where: $$r = \pm\ (p_x^2 + p_y^2)^{1/2} \qquad (10)$$

The value for $\emptyset_3$ can now be obtained by equating the 1,4 and 2,4 elements from (8) resulting in

$$\emptyset_3 = \arctan a_3/-d_4 - \arctan d/(e - d^2)^{1/2} \qquad (11)$$

where:
$$d = f^2_{11p} + f^2_{12p} - d^2_4 - a^2_3 - a^2_2$$
$$e = 4a^2_2 a^2_3 + 4a^2_2 d^2_4$$
$$f_{11p} = C_1 p_x + S1 p_y$$
$$f_{12p} = -p_z$$

The value for $\emptyset_2$ can now be obtained by using the following A matrices inverse and equating the 14 and 34 terms.

$$A_3^{-1} * A_2^{-1} * A_1^{-1} * T_6 = U_4 = A_4 * A_5 * A_6$$

$\emptyset_2$ can now be obtained:

$$\emptyset_2 = \emptyset_{23} - \emptyset_3$$

where $\emptyset_{23} = \arctan (w_2 f_{11p} - w_1 p_z) / (w_1 f_{11p} + w_2 p_z)$

$$w_1 = a_2 c_3 + a_3$$
$$w_2 = d_4 + a_2 s_3$$

5.0 DYNAMIC ANALYSIS

The simplified equations for the effective inertias as described by Paul (Reference 4) were derived for the manipulator. A discussion on the justification for elimination of inertia coupling, centripital, and coriolis forces are discussed in following paragraphs.

It was assumed that the response times of the joint servos decrease monotonically with increasing joint number. The joints then act in an uncoupled manner and it is not necessary to calculate inertia coupling torques. Centripetal and coriolis forces do not cause servo instability but only lead to position error offsets. These offsets occur at high speed, which will normally not be the case for an IVA robot.

We are interested then in the effective joint inertias, while ignoring gravity loading torques, due to the fact that operation will be conducted under free fall conditions. In simplifying the equations for inertias we will employ significance analysis. We will drop as many terms as possible in the expression for the inertias such that the final result is within 10% of the correct value.

The joint inertias are functions of the masses of the links and the radii of gyration. Actual values for the masses and radii of gyration can be obtained through measurement by using the functional form of the simplified equations we have obtained. This can be done by driving various joints at given torques and measuring the resulting accelerations for a number of different configurations of the manipulator. The resulting set of equations can then be solved for the masses and radii of gyration. We have estimated values for these based on an examination of the manipulator. This was primarily to determine those values which could be realistically set to zero in order to simplify the equations.

The dynamics equation for a manipulator may be obtained using Lagrangian mechanics

$$F_i = \sum D_{ij} q_j + I_{ai} q_i + \sum\sum D_{ijk} q_j q_k + D_i \qquad (15)$$

Where

F_i = torque or force acting at joint i

q_i = ith joint variable

q_i, q_i = velocity and acceleration, respectively, of joint variable i.

D_{ii}, D_{ij} = effective inertia and coupling inertia.

While ignoring all other forces except effective inertias, equation F_i reduces to:

$$F_1 = D_{ii} = \Sigma\, m_p \,\{[n^2{}_{pz}k^2{}_{pxx} + o^2{}_{pz}k^2{}_{pyy} + a^2{}_{pz}k^2{}_{pzz}] + [Pd_iPd_i] + 2[Pr_p(Pd_i \times P\partial_i)]\}$$

The calculations of the inertia torques are obtained through the use of homogeneous transformation A matrices for the arm and were given in the kinematic analysis section equations (1)- (6), and the radii of gyration $k^2{}_p$ and relative link masses are given in Tables 2 and 3, respectively. Because we are only interested in reaction forces at the base (joint 1) the effect inertia was found to be:

$$D_{11} = a + b + c + d$$

where:

```
a  =  (m1 * k1yy);

b  =  m2 * {[k2xx * (s2 * s2)] + [k2yy * (c2 * c2)]
        + [(a2 * a2) * (c2 * c2)]
        + [2 * x2 * a2 * (c2 * c2)]}

c  =  m3 * {[k3xx * (s23 * s23)]
        + [k3zz * (c23 * c23)]
        + (d3 * d3)
        + [(a3 * a3) * (c23 * c23)]
        + [(a2 * a2) * (c2 * c2)]
        + (2 * a3 * a2 * c23 * c2)
        + 2 * z3 * [(a3 * c23 * s23) + (a2 * c2 * s23)]}

d  =  masstotal4 * {[k4xx * (s23 *s23) * (c4 * c4)]}
        + [k4yy * (c23 * c23)]
        + [k4zz * (s23 * s23) * (s4 * s4)]
        + (d3 * d3)
        + [(d4 * s23) + (a3 * c23) + (a2 * c2)]
        * [(d4 * s23) + (a3 * c23) + (a2 * c2)]
        - [(2*y4) * (d4 * s23) + (a3 * c23) + (a2 * c2) * s23]}
```

$masstotal_4$ = mass of link 4 plus the payload (which is the LBF).

It was assumed that joints 5 and 6 remained fixed during manipulation of this large mass and, therefore, terms D_{66} and D_{55} were ignored.

6.0 NASTRAN MODEL

The Space Station finite element model from Reference 6 was executed on a VAX 11/780 computer. The NASTRAN model that was used in this analysis was based on Space Station configuration 1 using a transient forcing function input developed by a robot arm and crew member

The mass properties for configuration 1 are given in Table 4. The total mass of the Station is approximately 150,000 kg with the center of gravity located within node 2.

The sixth flexible mode (f12) involves a significant rigid body rotation of the manned core. The larger inertial mass resisting the rotation accounts for the lower frequencies for the configurations with the Life Science Module. The first mode in which the module cluster participates is approximately 2.0 Hz for the 100% and 50% berthing mechanisms stiffness cases, and 1.6 Hz for the 10% case. These values are well above the operating ranges of the robot indicating that the manned core will tend to behave as a rigid body during robot manipulation.

The fundamental frequency of the Station is 0.622 Hz, which falls within the lower region of the entire operating range of the IVA robot during the initial analysis. For the Robot arm manipulation below this frequency, the entire Station exhibits a rigid body mode of response.

7.0 LOAD CASES

The load cases of both a robot arm and a crew member manipulating the LBF were evaluated. In the case of the robot arm manipulating the IBF, we looked at three different path trajectories. They consisted of planar motion in purely x, purely y, and through all three planes. In the case of crew manipulation, we assumed that the furnace was moving at a velocity of 0.154 m and the facility came to a stop by a crew applying an opposing force coupled between himself and the Space Station.

The effects of structural damping are significant only when the disturbance frequency coincides with a natural frequency of the station. Structural damping will reduce the amplitude of the response to the disturbance in the neighborhood of these natural frequencies. The IVA robot operates from 0.004 g to 1.3×10^{-6} g, and its corresponding operating frequencies lie between 0 Hz and 0.743 Hz (see Section 2.4). The Station configuration contains natural frequencies down to 0.622 Hz. This means that the structural damping factor plays an important part in the amplitude of the disturbance at the higher operating frequencies of the IVA robot.

The Space Station berthing mechanisms represent the primary load path for disturbance transfer from one Station element to another. Because of this, their stiffness characteristics are significant factors in experiment excitation response. Berthing mechanism stiffness data were not readily available, nor were there sufficient data to calculate accurate stiffness values. Consequently, a range of values (100%, 50%, and 10% of the module stiffness) was chosen that would cover the actual stiffness when its design is more clearly defined. These values were applied parametrically to each of the Station configurations and their respective load cases.

8.0 RESULTS

The transient response analysis was performed using the forcing function generated by the robot arm manipulating the LBF. The forcing function was input into the Space Station NASTRAN model to obtain a dynamic response in association with acceleration disturbances throughout the USL.

The robot arm forcing function was developed by giving the kinematic model starting and end points in x-y-z coordinates of the trajectory and the required velocity. The dynamic model program then calculated time and acceleration to complete the task. Joint motor accelerations were then calculated, which resulted in reaction forces at the base of the robot. The forcing function generated at the base of the robot by purely x and y planar motions of the end effector are shown in Figures 3a and 3b, respectively. A third trajectory was developed using an end effector trajectory through all three planes and resulting forcing function shown in Figure 3c.

Purely x and purely y forcing functions were then input into the Space Station NASTRAN model with the results of the acceleration disturbances shown in Figures 4a, 4b, 4c, 4d, 5a, 5b, 5c, and 5d for the first two cases mentioned above at grid points of interest.

Another forcing function case was then generated using a shape optimal trajectory to represent a more sinusoidal function, which resulted in a disturbances to the station at an acceptable level for experiment operation as shown in Figures 6a and 6b.

Figures 7a, 7b, 7c, and 7d illustrate the effects of the crew 50 lb_f forcing function applied at grid point 126 over a period of three seconds to bring the LBF to rest. It can be seen that the level of disturbance seen by the station after the force is applied does not exceed 15 micro-g's (15×10^{-6}).

Based on these results it is apparent there is two different frequency responses spectrums. A relative constant low frequency response around 0.70 Hz was generated from all the forcing functions, which is just above the Space Station fundamental frequency (0.623 Hz).

The sinusoidal forcing function generates a variable frequency response which is a function of the magnitude of the forcing function input. This response produces a lower frequency which decreases with decreasing force amplitude.

The results also show that the microgravity acceleration response levels range from 1.3 micro-g's to 0.004 G's and are a function of profile and method of disturbance input to the NASTRAN model.

The forcing functions applied in these cases assumed no type of isolation system at the base of the robot arm. This produces accelerations and displacements to the space station of much greater magnitude that would probably actually been seen in the operational Space Station configuration. So when taking into account the stiffness of robot mounting hardware to the Space Station, preliminary results have shown that robot manipulation g-level disturbances decrease as much as 100 times.

9.0 CONCLUSIONS AND RECOMMENDATIONS

Based on reaction forces from the robot base torques, the robot should not operate as a function of end effector velocity but on base torque measurements. The disturbances generated by the robot when the end effector maintained a certain velocity exceeded the microgravity envelope desired. A sinusoidal forcing function comparable in magnitude resulted in almost two orders of magnitude less acceleration disturbance. This implies that the robot should not necessarily take a straight line trajectory, but a shaped optimal trajectory that would minimize reaction forces at the base, given efficient space. It is also suggested that the robot controller transfer function should use motor acceleration feedback and mass distribution as the feedback paramaters instead of a function of end effector velocity for the case studied.

10.0 ACKNOWLEDGEMENT

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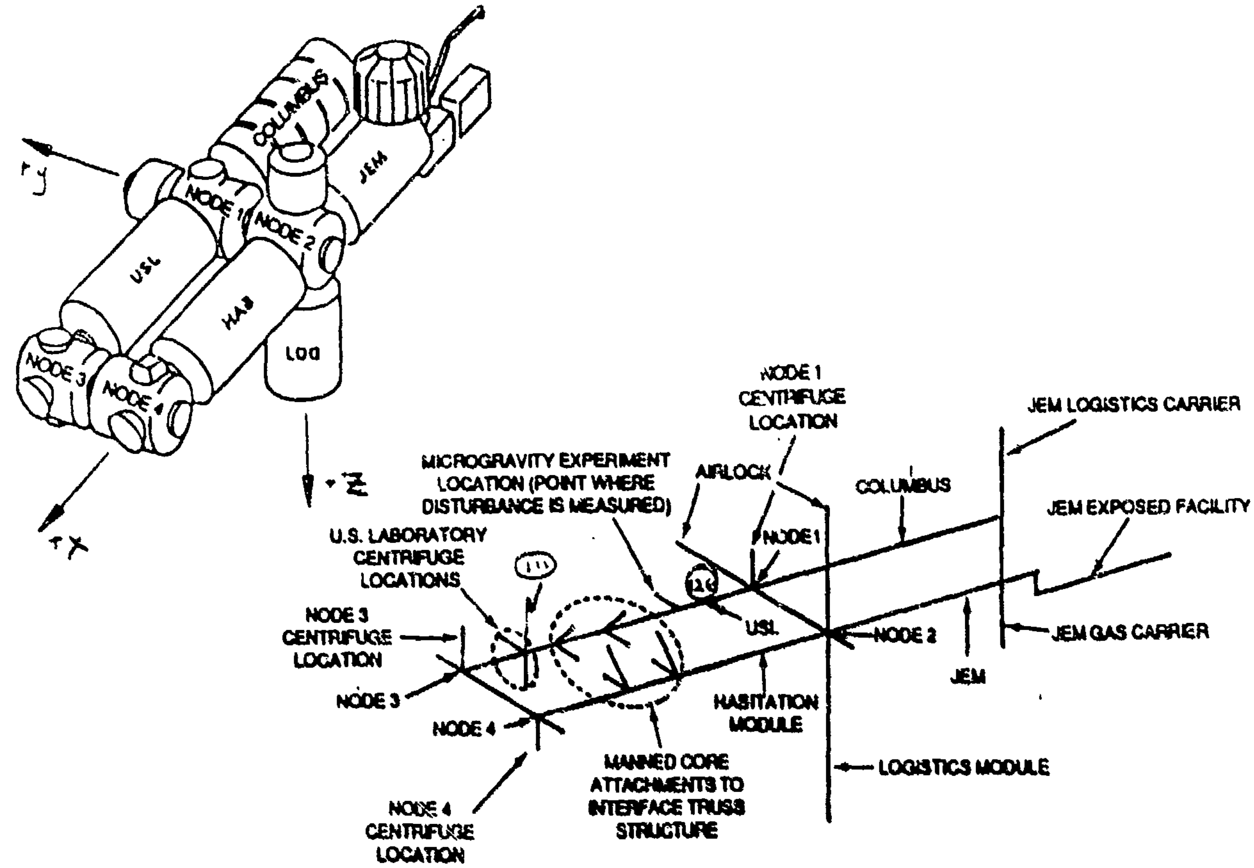


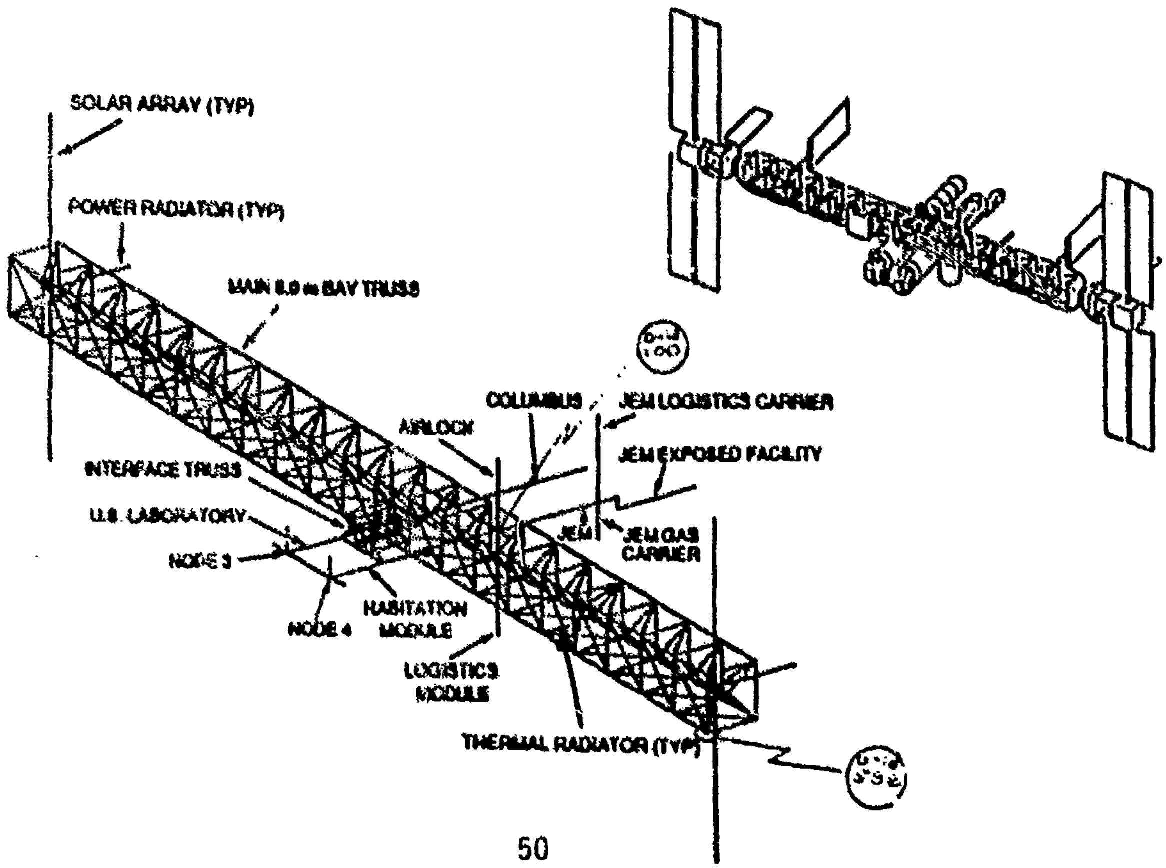
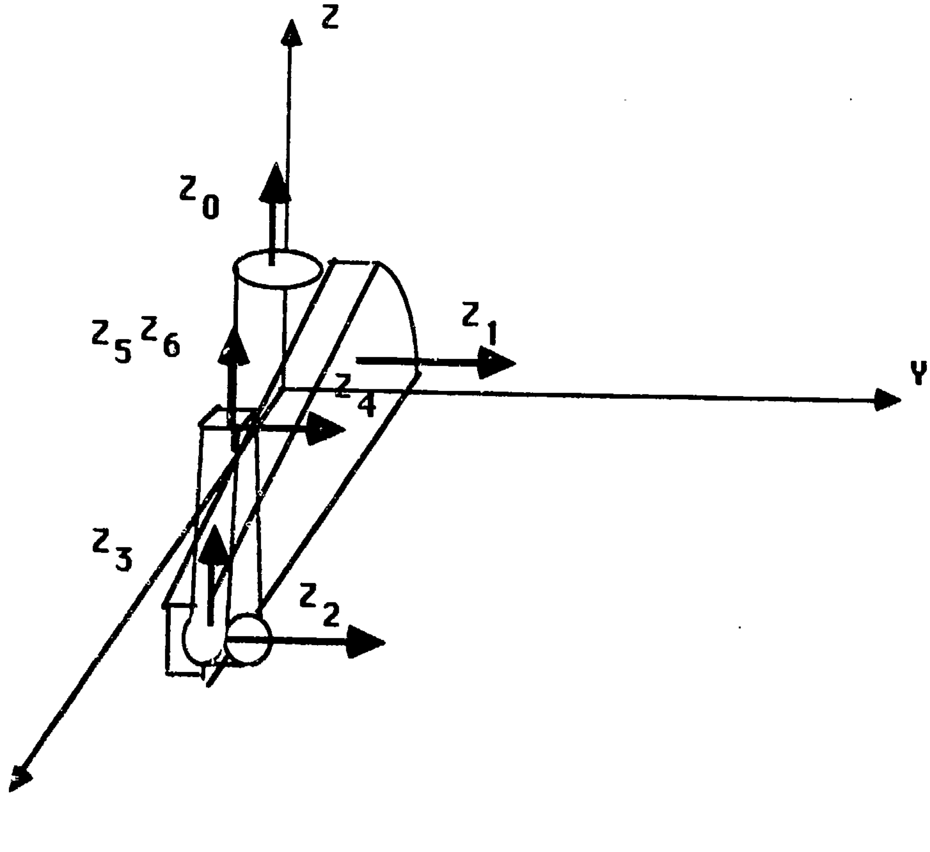


FIGURE 1. Space Station Configuration #1



$$An = \mathrm{Rot}(z,\theta)\ \mathrm{Trans}(0,a,0)\ \mathrm{Rot}(x,\alpha)$$

$$An = \begin{bmatrix} C_\theta & -S_\theta & 0 & 0 \\ S_\theta & C_\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & a \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_\alpha & -S_\alpha & 0 \\ 0 & S_\alpha & C_\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$An = \begin{bmatrix} C_\theta & -S_\theta C_\alpha & S_\theta S_\alpha & -aS_\theta \\ S_\theta & C_\theta C_\alpha & -C_\theta S_\alpha & aC_\theta \\ 0 & S_\alpha & C_\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

FIGURE 2. ROBOT KINEMATIC MODEL

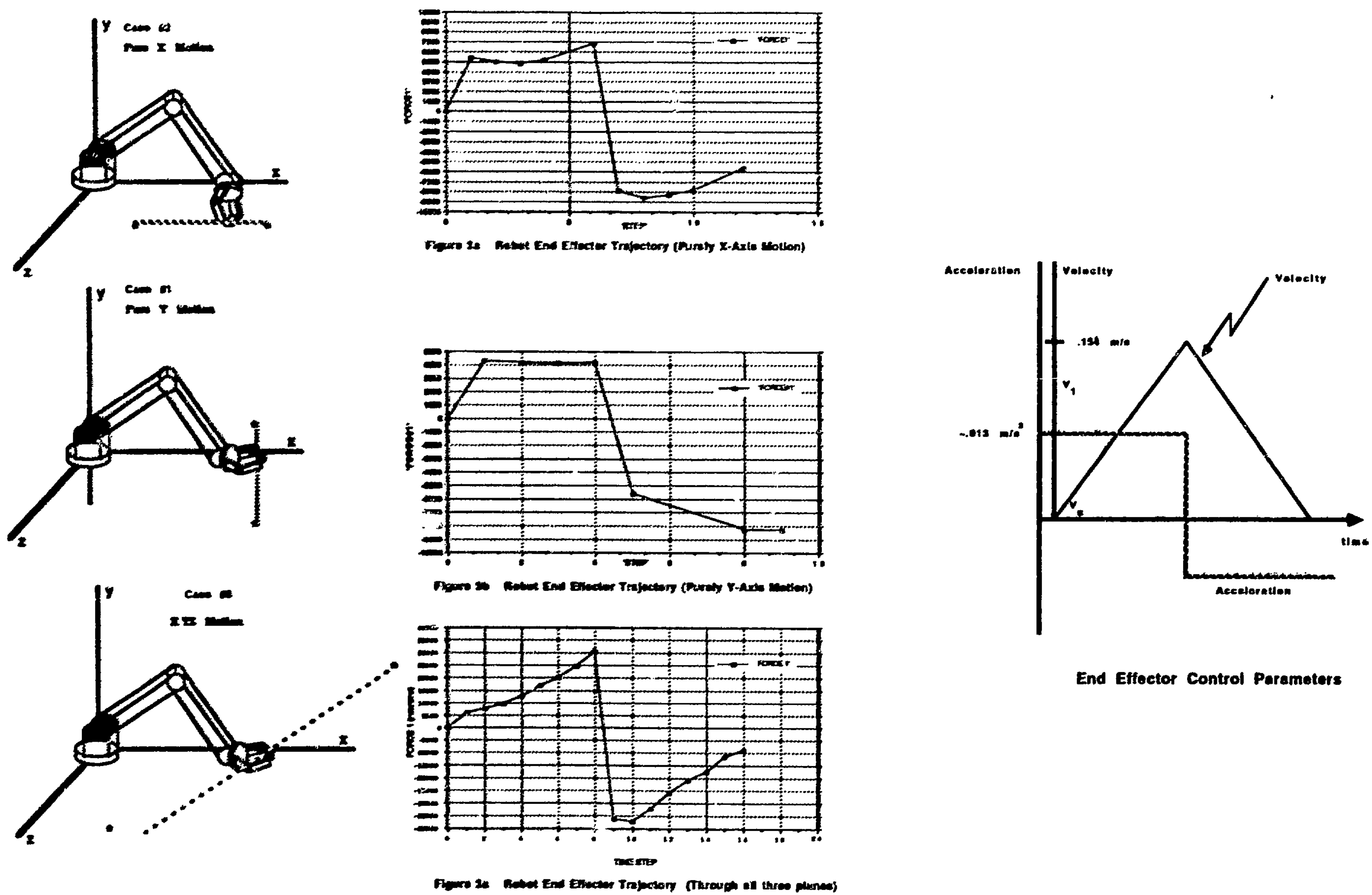


Figure 3a Robot End Effector Trajectory (Purely X-Axis Motion)

Figure 3b Robot End Effector Trajectory (Purely Y-Axis Motion)

Figure 3c Robot End Effector Trajectory (Through all three planes)

Figure 3 Robot Arm Forcing Functions

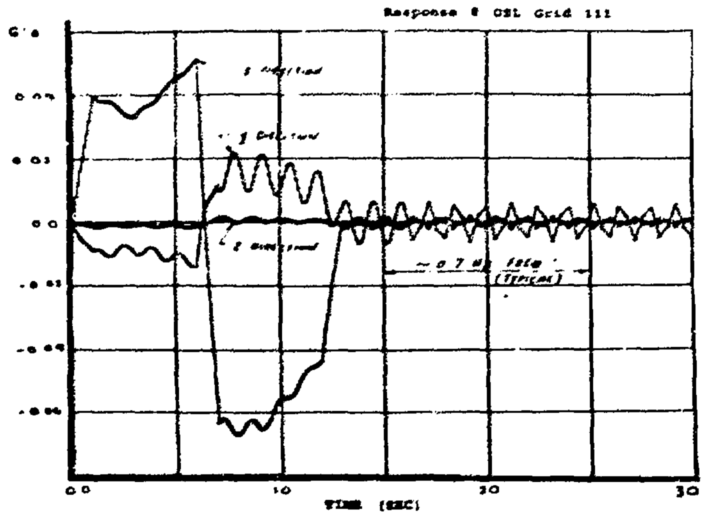


Figure 4a X-Axis Force applied at Grid 126

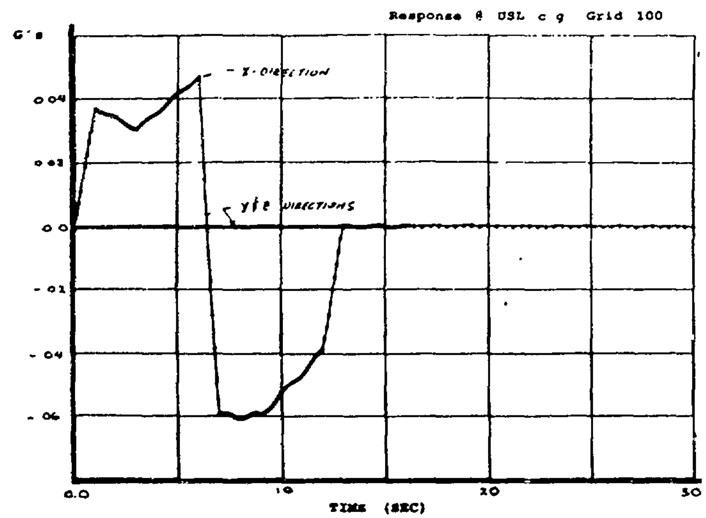


Figure 4c X-Axis Force applied at Grid 126

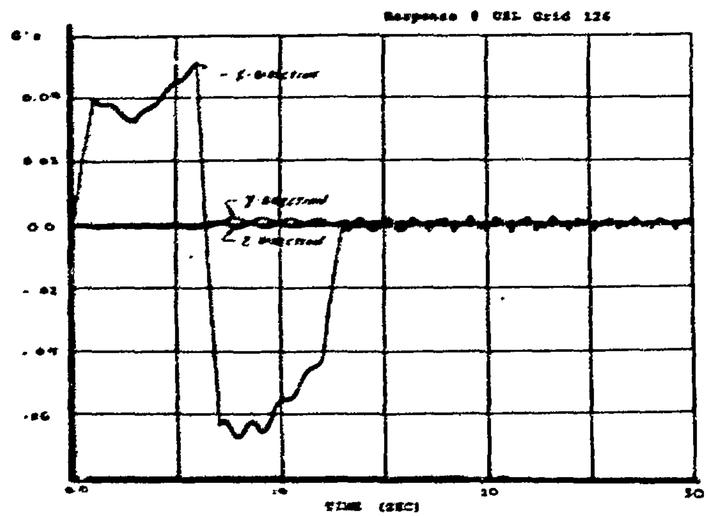


Figure 4b X-Axis Force applied at Grid 126

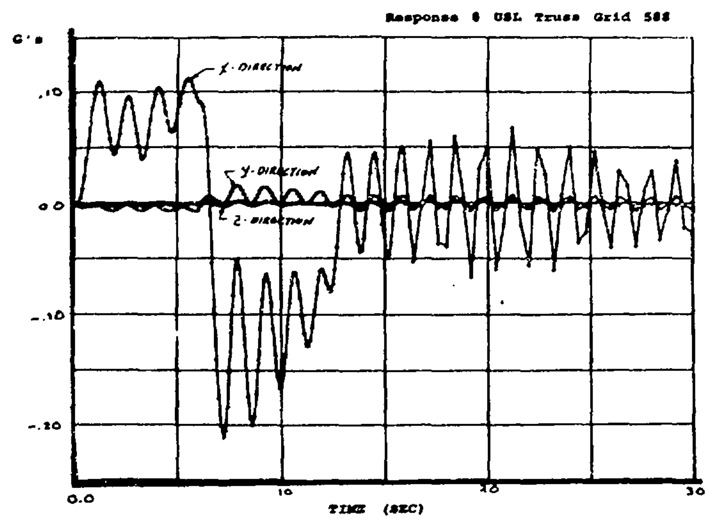


Figure 4d X-Axis Force applied at Grid 126

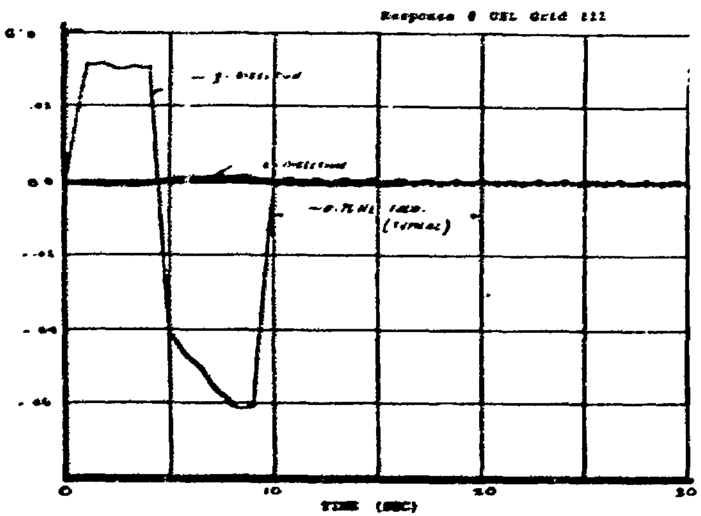


Figure 5a Y-Axis Force applied at Grid 126

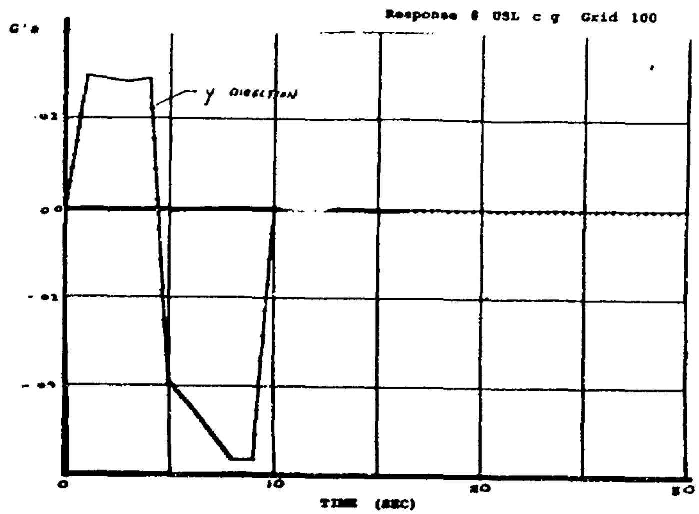


Figure 5c Y-Axis Force applied at Grid 126

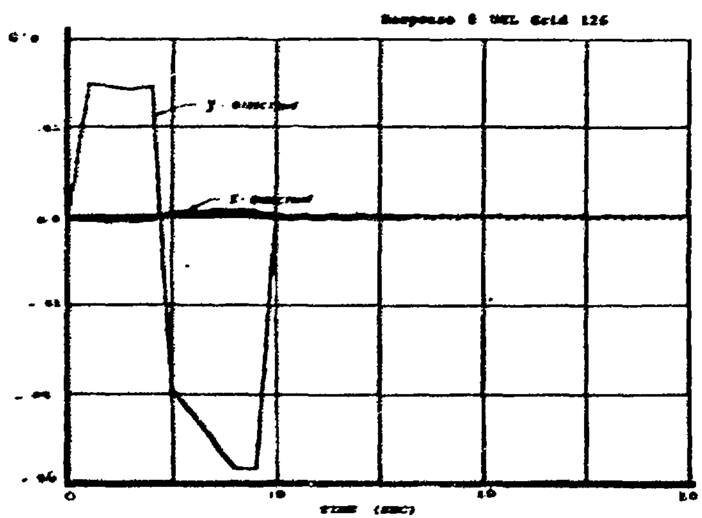


Figure 5b Y-Axis Force applied at Grid 126

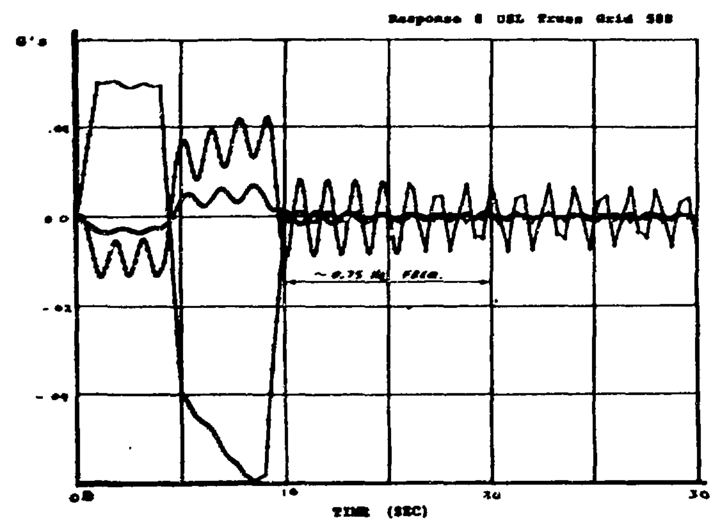


Figure 5d Y-Axis Force applied at Grid 126

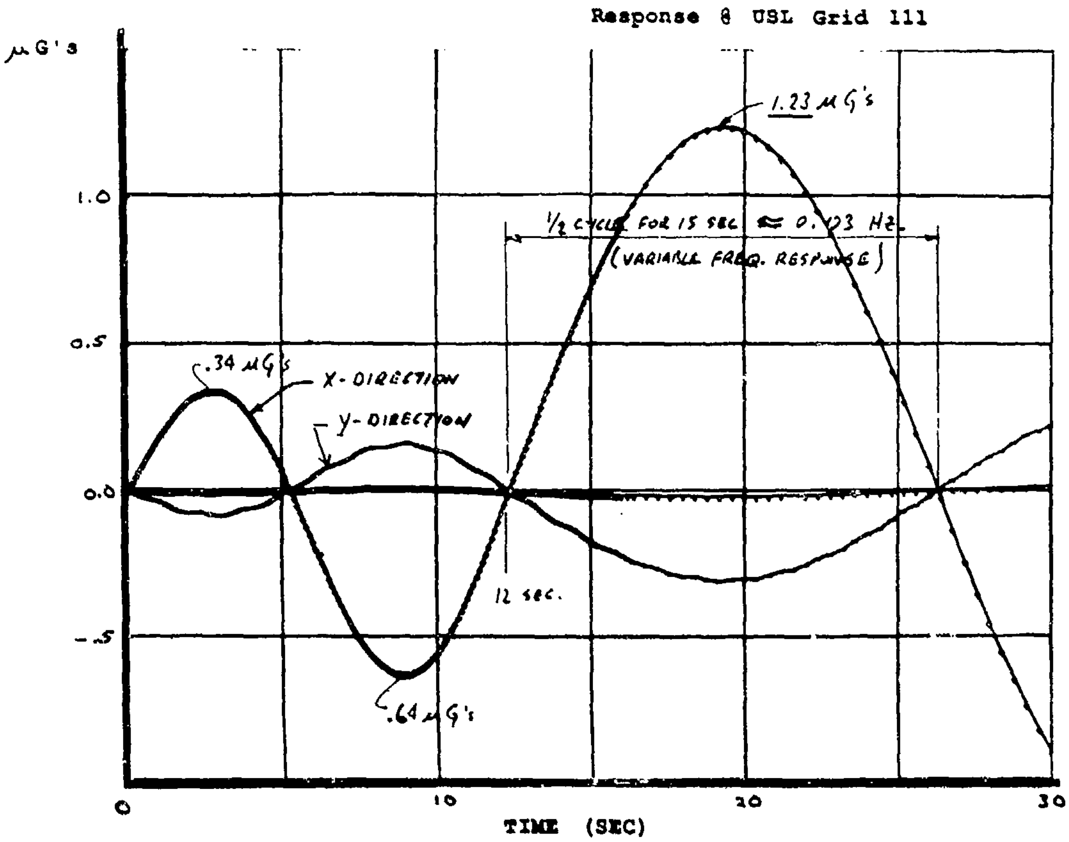


Figure 6a Sinusoidal Force applied at Grid 126

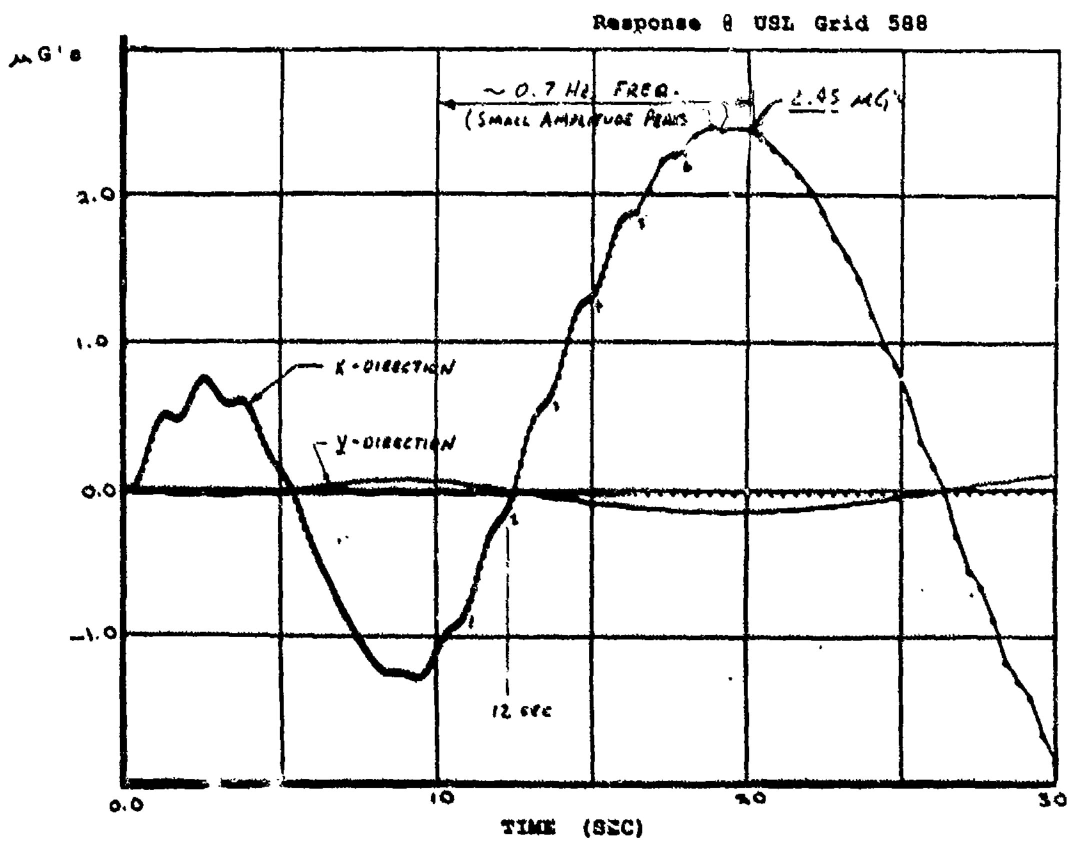


Figure 6b Sinusoidal Force applied at Grid 126

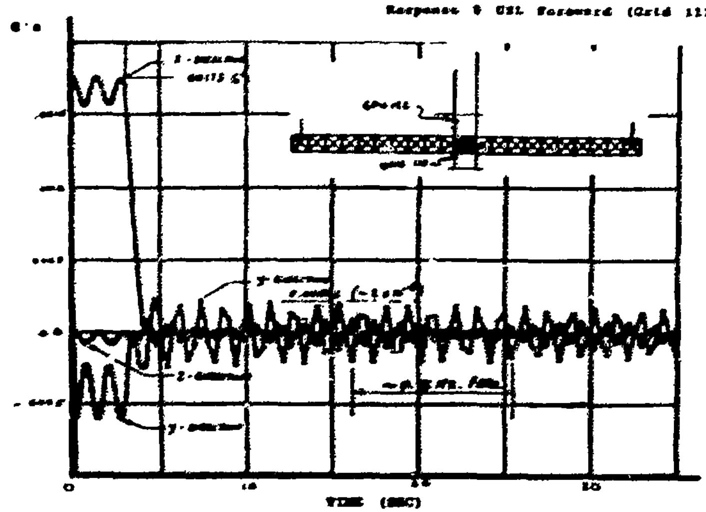


Figure 7a Crew Motion Force applied at Grid 126

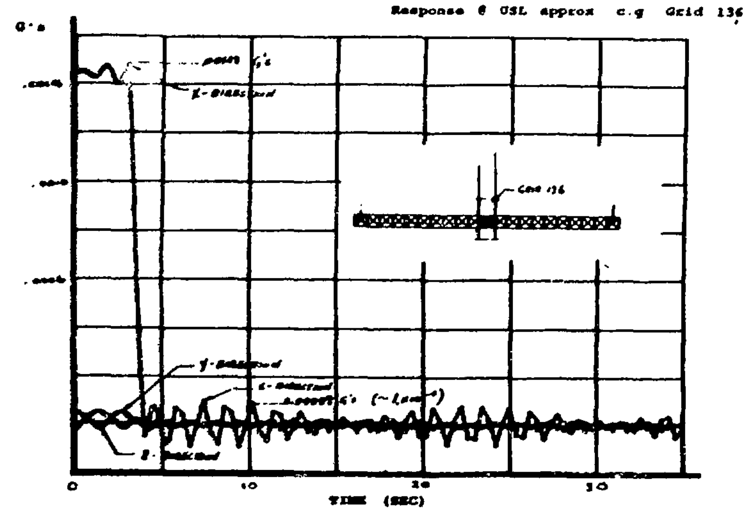


Figure 7c Crew Motion Force applied at Grid 126

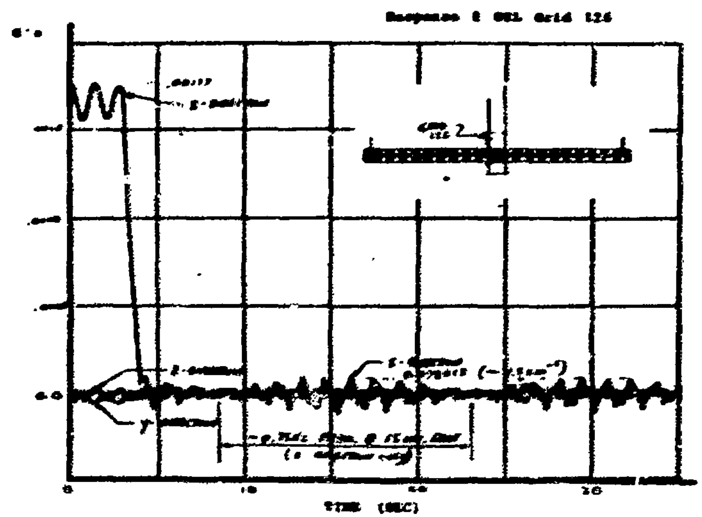


Figure 7b Crew Motion Force applied at Grid 126

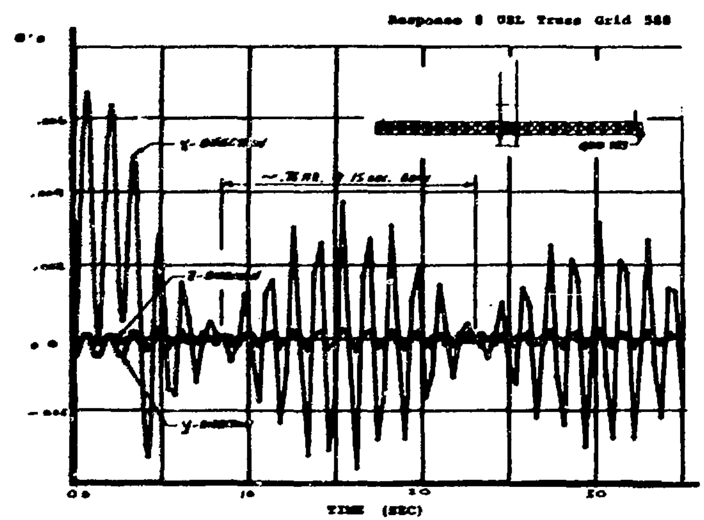


Figure 7d Crew Motion Force applied at Grid 126

TABLE 1. Link Parameters

$LINK_1$	VARIABLE	α	a	d
1	θ_1	-90	0	0
2	θ_2	0	a_2	0
3	θ_3	90	a_3	d_3

a_2 = 17.000 a_3 = .75
d_3 = 4.937 d_4 = 17.00

TABLE 2. Radii Of Gyration

Link	k^2_{xx} (cm^2)	k^2_{yy} (cm^2)	k^2_{zz} (cm^2)
1	451	451	57.9
2	565.7	1847	1408
3	672.8	679.1	36

TABLE 3. Relative Link Mass and First Moments

Link	Plate Area (cm^2)	$\bar{x}$ (cm)	$\bar{y}$ (cm)	$\bar{z}$ (cm)	Relative Mass
1	1910	0	0	8	33.5
2	4408	-21.6	0	21.75	77.3
3	2070	0	0	21.6	36.3

TABLE 4. Space Station Mass Properties

Property	
MASS	1.45E+05
Ixx	1.19E+07
Iyy	1.54E+07
Izz	2.47E+07
x cg	1.191
y cg	2.788
z cg	.512

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AN AUTOMATED PROTEIN CRYSTAL GROWTH FACILITY ON THE SPACE STATION

April 1988

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ABSTRACT

This paper will address the need for an automated Protein Crystal Growth experiment on the Space Station and how robotics will be integrated into the system design. This automated laboratory system will enable several hundred protein crystals to grow simultaneously in microgravity and will allow the major variables in protein crystal growth to be monitored and controlled during the experiment. Growing good quality crystals is important in determining the complete structure of the protein by X-Ray Diffraction. This information is useful in the research and development of new medicines and other important medical and biotechnological products.

Previous Protein Crystal Growth Shuttle experiments indicate that the microgravity environment of space allows larger crystals of higher quality to be grown, as compared to the same crystals grown on the ground. It is therefore important to have a laboratory in space where protein crystals can be grown under carefully controlled conditions so that a crystal type can be reproduced as needed.

1.0 INTRODUCTION

Proteins are found in all living tissue. Knowing the structure of certain proteins is important in the research and development programs of the medical and other biotechnical fields. Figure 1 shows the protein, Canavalin, in solution.

Once a protein crystal is formed, its structure is determined by X-Ray Diffraction, thus growing good quality crystals is important in this process. Crystals grown in a ground based laboratory are affected by convection currents in the protein droplet produced by gravitational fields. These convective currents can be controlled under microgravity conditions.[1]

Preliminary studies indicate that microgravity can improve crystal homogeneity and decrease the number of defects in crsytals. An experiment that flew on Spacelab 1 by Littke and John showed that space grown protein crystals are considerably

1. Bugg, Charles E., DeLucas, Lawrence J., and Suddath, F. L., "Preliminary Investigations of Protein Crystal Growth Using the Space Shuttle," University of Alabama in Birmingham, 1985.

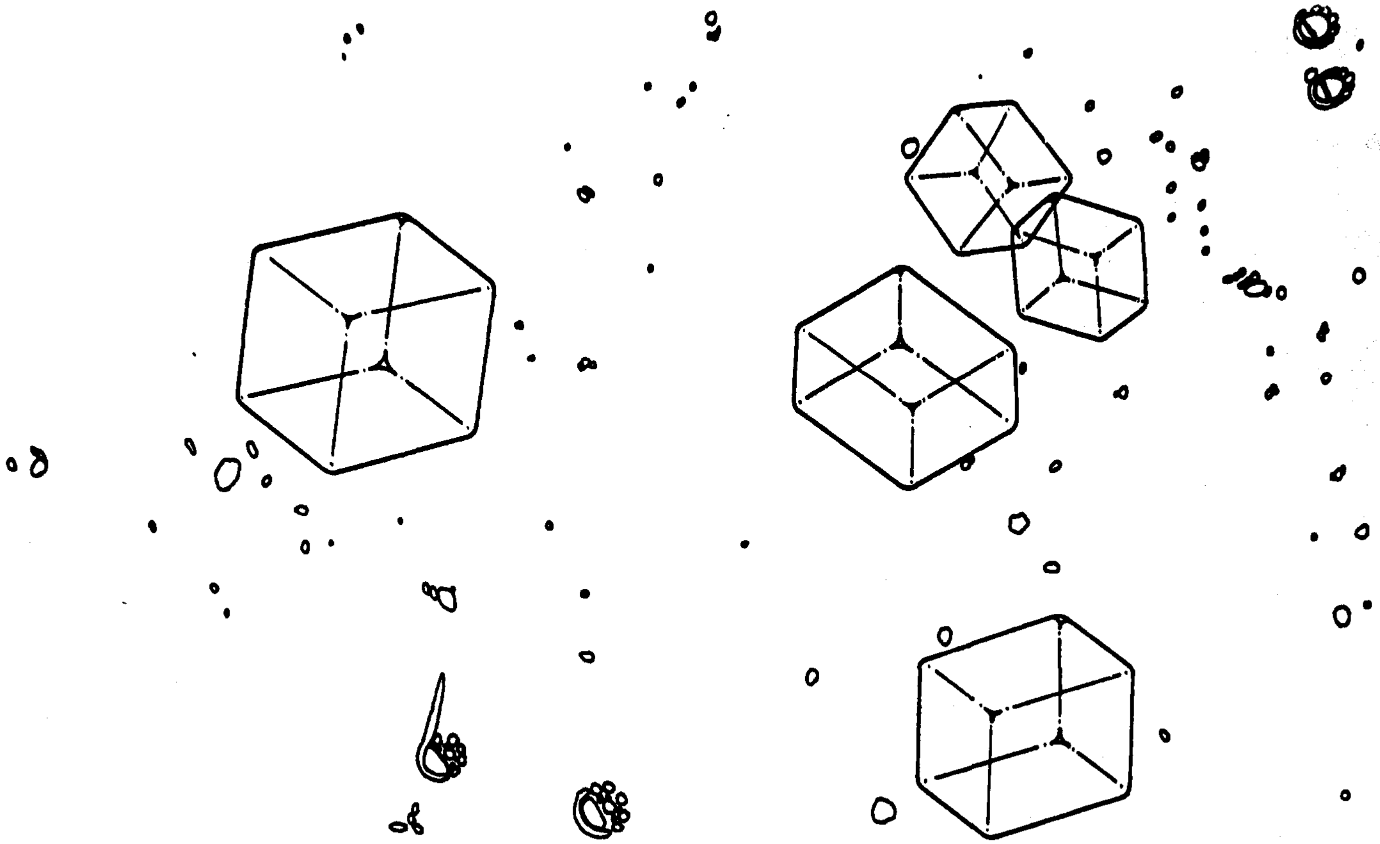

Figure 1. Canavalin Protein Crystals in Solution

larger than crystals grown under the same conditions on the ground.[2] Since Spacelab 1, a hand-held protein crystal growth facility was flown in April, 1985, which produced the largest, highest quality crystals grown thus far.[3] These results have only strengthened the belief that major benefits can be gained from growing protein crystals in microgravity.

1.1 Techniques for Growing Protein Crystals

There are several techniques of growing protein crystals. They are listed as follows:

1. Vapor Diffusion - "Hanging Drop Method" - Water vapor is transported from a protein droplet (20 μL) by difference in vapor pressure when the drop is placed close to a larger volume of precipitant solution (2 mL). As the water evaporates the protein concentration increases initiating the formation of a crystal.

"Sandwich Method" - A chamber is divided into three sections by two semi-permeable plates. The protein droplet is placed between the two places with air on one side and precipitant solution on the other side.

2. Liquid Diffusion - The protein and precipitant solutions are brought into contact with each other and are allowed to mix by diffusion.

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2. Littke, W. and John, C., "Protein Single Crystal Growth Under Microgravity," Science, 225, 1984, pp. 203-204.

3. Bosarge, James (Editor), "UAB News Release," University of Alabama in Birmingham, May 1985.

3. Dialysis Method - The protein solution is placed within a bag made of a dialysis membrane. This bag is placed in a precipitant solution where movement of the precipitating agent through the membrane initiates the crystal formation.

Currently, the most popular method is the "Hanging Drop" method. All existing hardware for microgravity experiments is designed for this method, because it has the largest ground laboratory data base.

1.2 The Protein Crystal Growth Experiment

The Protein Crystal Growth Experiment is divided into four phases. Development of the experiment hardware began as a simple hand-held unit and has evolved to the proposed Space Station facility.

1. Phase I - In this first phase, a basic experiment was set up, mainly to demonstrate whether or not growing protein crystals in microgravity produced crystals of larger size and higher quality. The experiment was housed in a small, hand-held device containing vapor diffusion growth chambers where a protein droplet was placed on a pedestal within the chamber and monitored periodically. Figure 2 shows this unit which was flown on the Shuttle four times.[4] In this experiment, the protein and precipitant solutions were pre-mixed and late-loaded into the Shuttle twenty-four (24) hours before launch. The samples were hand deployed by the astronaut in a non-controlled thermal environment, and photographs were taken periodically during the experiment. The crystals grown during this Shuttle mission did prove to be larger in size and of higher quality than their ground-based counterparts. The first Shuttle flight of this experiment was on April 12, 1985.

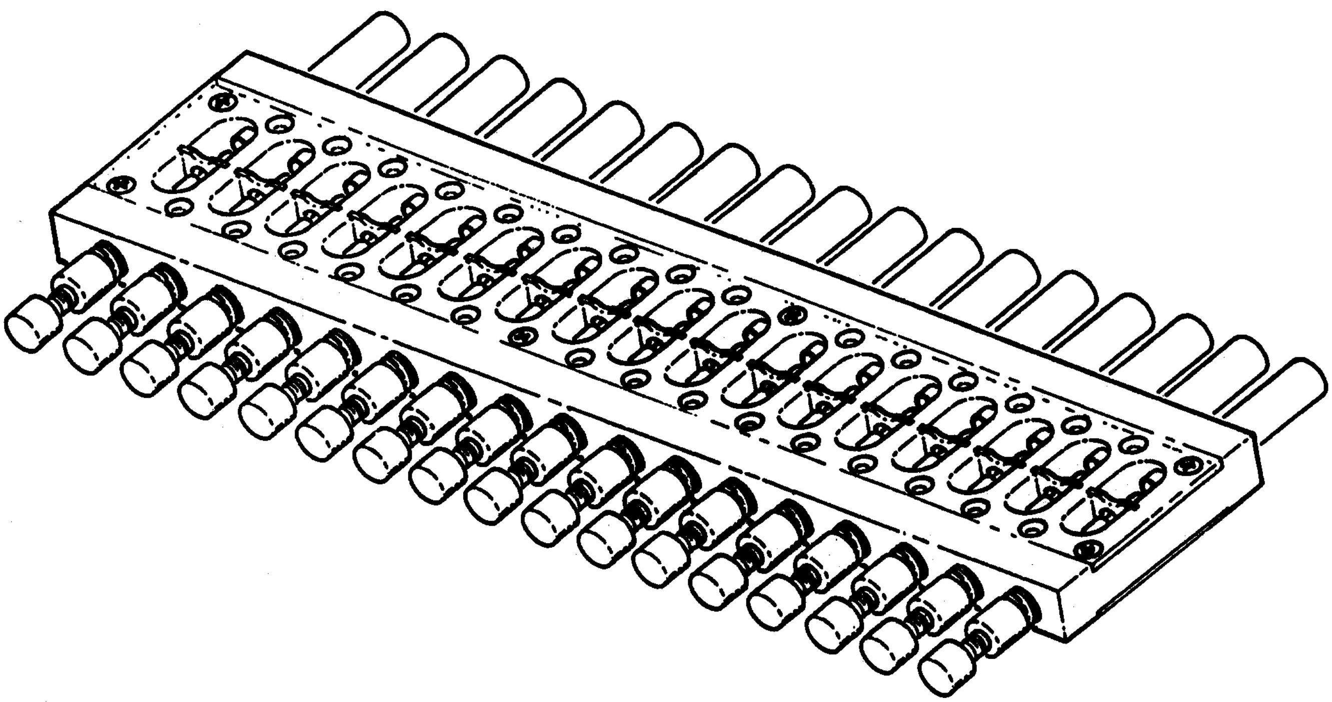

Figure 2. Phase I Protein Crystal Growth Flight Hardware

4. Herrmann, F. T., "Advanced Protein Crystal Growth Flight Hardware for the Space Station," AIAA, 1988.

2. Phase II - Based on the results of Phase I, the same basic hardware design is used, but now the samples are kept in a thermally controlled refrigerator/incubator. Also, the protein and precipitant solutions are kept in separate chambers using a double-barreled syringe and are deployed by a ganged mechanism that will simultaneously uncap and deploy twenty (20) samples. Figure 3 shows the details of one of the trays that holds the growth chambers.[4] To monitor and take photographs of the protein crystals during the experiment, the astronaut has to manually pull the tray out, causing vibration to the chambers which may jeopardize the growth development of some crystals. The launch date for this Phase II hardware is To Be Determined.

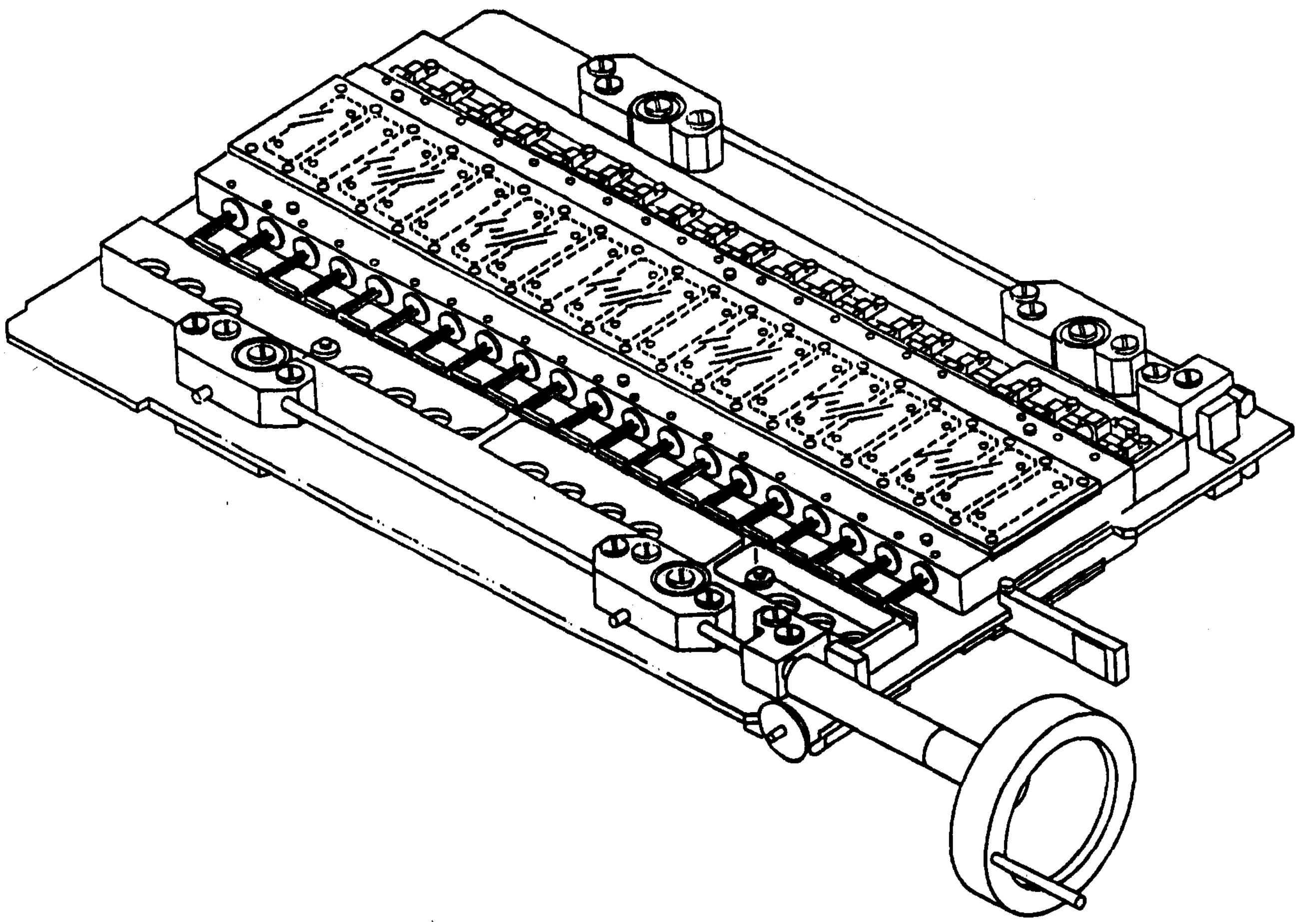

Figure 3. Phase II Protein Crystal Growth Flight Hardware

3. Phase III - In this phase, an additional number of growth chambers will be added to the trays of the Phase II hardware. Results of the Phase II launches will be incorporated into the Phase III hardware development.

4. Phase IV - Phase IV is an automated system which allows the protein and precipitant solutions to be loaded separately. Once the experiment is started, these solutions are automatically mixed and dispensed into individual growth chambers. These chambers are housed in trays that are mounted to the walls of a Spacelab double rack. Each tray will be kept at a certain temperature as specified by the experimenter. Each chamber will be monitored periodically using microscopic video (Imaging) and some or all of the following desired monitoring techniques:

refractive index, UV absorption, laser light scattering, and pH measurement. All monitoring must be done without disturbing the protein drop and will be the biggest driver for the final experiment design. The automated system is designed for Spacelab with transition to Space Station. Figure 4 shows one concept of a Phase IV system. A detailed conceptual study was performed, and the results of that study will be covered in this section.[5]

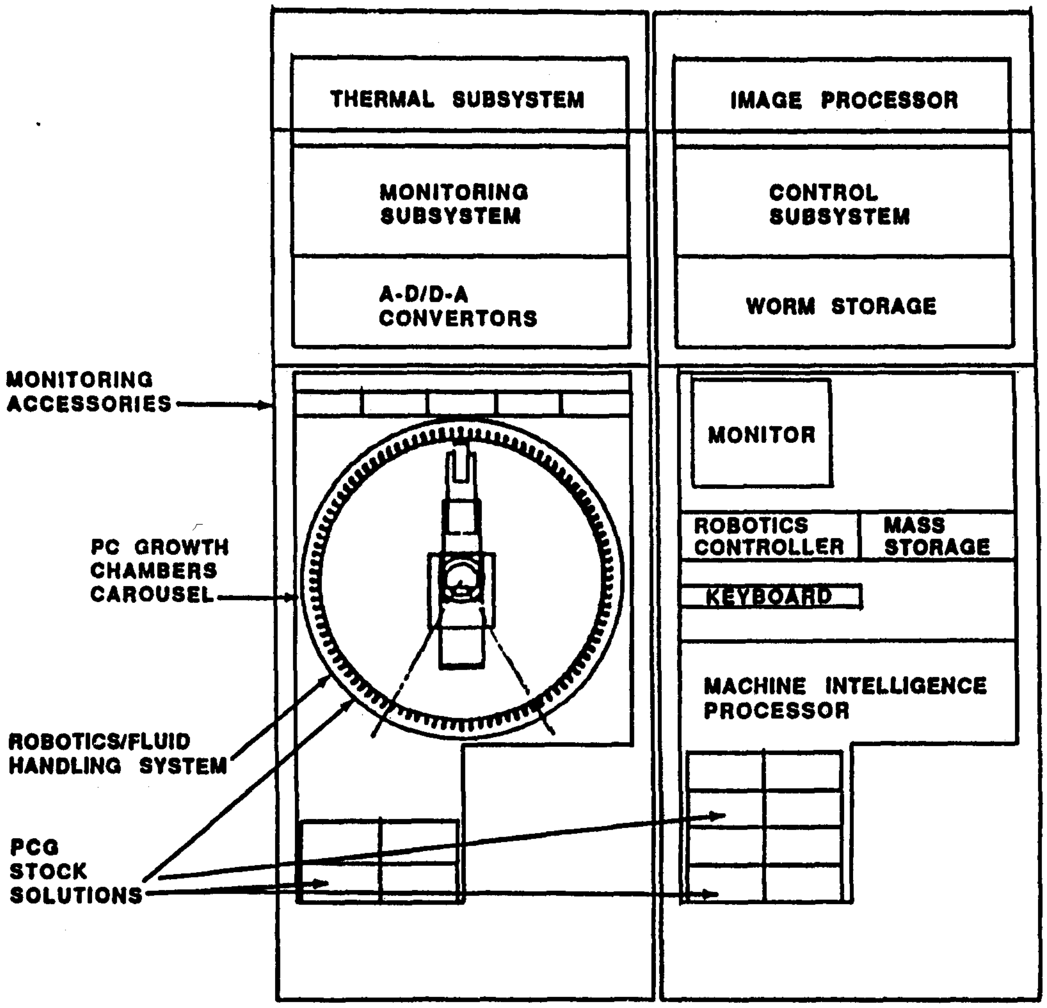

Figure 4. Advanced Protein Crystal Growth Facility Concept Shown in Two (2) Space Station Double Racks

The preliminary science requirements of the advanced Space Station crystal growth facility are:

1. After Low-G is obtained, the protein and precipitant solutions are mixed.
2. Protein droplets are then dispensed into appropriate chambers.
3. Several hundred chambers operate simultaneously with the flexibility of dynamically changing growth conditions.
4. Monitor crystal formation periodically as specified by the experimenter.
5. Stop crystal growth at appropriate time with a quench solution and store crystal for analysis on the ground.

5. Herrmann, M. C., Strider, D., Philips, A., Tucker, S., Horan, C., and Blevins, H., "A Concept for a Fully Automated Laboratory for Spacelab/Space Station," Marshall Space Flight Center, 198?.

There are several monitoring techniques desired in this experiment. Some require the development or application of new technology and are being studied by several groups under contract. Below is a list of these techniques:

1. Microscopic video of the protein drop.
2. pH measurement of the drop.
3. Refractive index to measure salt concentration of drop.
4. UV absorption to determine how much protein is in drop.
5. Laser light scattering to study nucleation in the drop.
6. Temperature measurement.

The Advanced Protein Crystal Growth Facility is a sophisticated microgravity laboratory which has high potential for utilizing state-of-the-art robotics and automation. One example of this is in the mixing of the precipitant and protein solutions in orbit. Two methods considered in the preliminary study are a fluid handling system that would prepare samples and pump the microliter quantities through tubing to the appropriate growth chamber, and a robot emulating man in the laboratory using syringes for mixing and deploying solutions. It is generally felt that a hybrid system using fluid handling and robotics will yield the best results.

A lot has been said about the growth chamber that houses each protein droplet during the experiment. The chamber design will be greatly affected by the results of the monitoring technique studies. Figure 5 shows the evolution of the growth chamber proposed in the conceptual design study. The chamber is designed to be robot friendly while remaining flexible for changing experiment requirements.

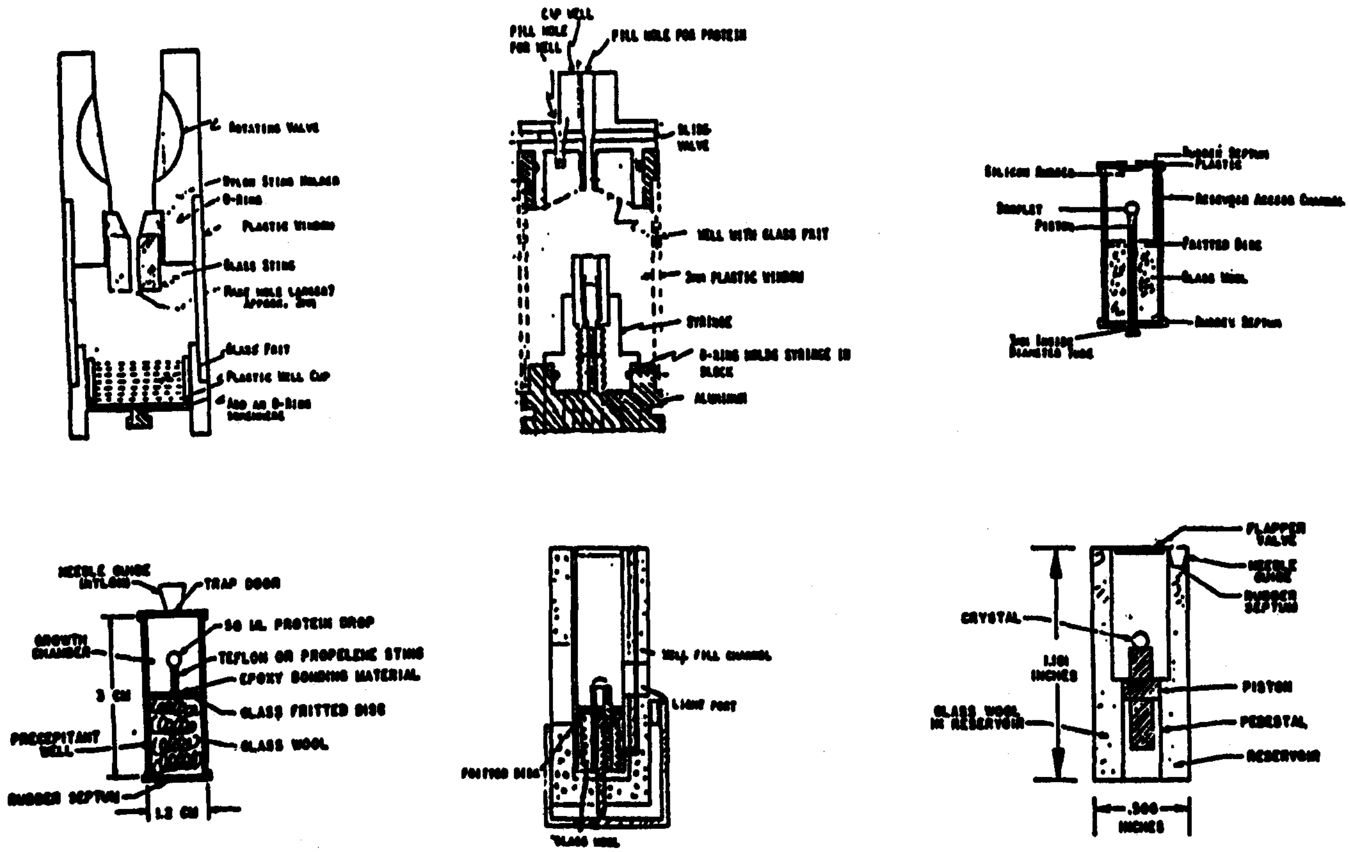

Figure 5. Evolution of the Protein Crystal Growth Chamber

One question that was addressed during the preliminary design study was should it be partially or fully man-tended. The study recommended that the advanced facility should be fully automated with minimal crew interaction. The reasons for this conclusion are:

1. Space Station crew members have a limited amount of time per experiment.
2. The complexity of the experiment with hundreds of samples running simultaneously lends itself to automation.
3. Could set a precedent for other advanced laboratories in space.
4. Opens the door for use of telescience where the experiment can control the experiment from the ground.

1.3 Summary

Protein Crystal Growth experiments previously flown on the Shuttle have clearly demonstrated the benefits microgravity has on the size and quality of the crystals, thus, enabling good definition of the protein structure by X-Ray Diffraction so researchers in the medical and other biotechnical fields can use this information to benefit mankind.

There is also a need for an advanced laboratory on the Space Station to grow protein crystals under a tightly controlled environment which will enable reproducibility of a crystal when needed. This facility is a natural candidate for development of a highly sophisticated automatic lab system utilizing new and innovative technology.

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Session II Program B

Strategies for Deployment

Chair: J. L. Prater, USAMICOM/RDEC

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Keynote Speaker: Colonel J. D. Petty, Director
Advanced Systems Concepts Office

Presented at the Conference on Space and Military
Applications of Automation and Robotics

21-22 June 1988 GACIAC PR 88-02

ARMY TACTICAL ROBOTICS ON THE BATTLEFIELD "AN INTEGRATION OF CONCEPTS"

21 June 1988

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ABSTRACT

This paper is a brief overview of MICOM's Battlefield Robotics activities. It includes a description of the Army battlefield robotics tasks, and a list of robotics missions and examples. There is a discussion of the existing robotic programs from which technical requirements have been derived. The paper presents a hierarchy of battlefield robotics and discusses the technical barriers associated with this progression. In summary, the challenges facing Government, Industry and Academia are presented.

The AMC community (led by the Human Engineering Laboratory (HEL)) began efforts in late 1980 to determine how robotics could be used on the battlefield of the future. This paper contributes to and expands that discussion through an integration of concepts, setting the stage for new discussion and thought in the emerging field of Automation and Robotics (A&R). Robot missions will be described and related to specific mission areas. Specific examples of efforts employing robotic concepts and techniques that could accomplish certain robotic missions are described. The User's rather than the developers point of view is employed.

Technical requirements for battlefield robots are complex and challenging, but not impossible. A hierarchy of battlefield robots exists which describes required capabilities and benefits to be gained from the introduction of robots onto the battlefield. Current technical limitations will result in years of evolutionary growth of robotic capabilities. In this light, challenges exist for the Government, Industry and Academia.

Three major tasks must be accomplished on the integrated battlefield: decide, detect and deliver (Figure 1. - all figures and tables can be found at the end of this report). Commanders must decide which major targets or complexes to attack, the targets must be found and finally destroyed or rendered ineffective. Smart Munitions (SM) are only one example of a lethal mechanism for implementing these tasks. Robotic missions can be performed in all mission areas including non-battlefield tasks such as manufacturing, training, and logistics. Savings can thus be gained in investments, support costs, and personnel. For the purpose of this paper however, these topics will be limited to the discussion of battlefield robotics.

Figure 2., relates the three mission areas of the Army, Combat Arms, Combat Support, and Combat Service Support, to their respective missions. Notice that many of the missions in each mission area are the same. This allows for system modularity and for concepts to serve multiple mission areas; thus providing an advantage both tactically on the battlefield and in financial savings. Shown in boxes, are those missions which currently have congressional restrictions:

> "The conferees agree that development and demonstration of the Tactical Robotics Vehicle may be continued only as they relate to the role of that vehicle limited to reconnaissance. No funds provided for the fiscal year 1988 and 1989 are to be used for development of the vehicle as a weapons platform or carrier."

Currently efforts are being made by the Army Material Command (AMC) and the Training and Doctrine Command (TRADOC) to remove these restrictions. Related non-battlefield tasks are shown at the bottom of Figure 2.

Examples where robotic concepts have been incorporated into military systems can be found in many programs being developed at MICOM. The Fiber Optic Guided Missile System (FOG-M), shown in Figure 3., has a remote control capability and the ability to visually receive in real time battlefield conditions and other feedbacks. The operator then uses this information to perform antiarmor and anti-helicopter missions. Figure 4., shows a variety of remotely controlled Unmanned Aerial Vehicles (UAV), which are used to perform surveillance tasks and other combat missions.

Not shown, are the Precision Deep Attack Missile System (PDAMS) and the Teleoperated Mobile Platform (TMP). PDAMS is a technology base program with the goal of solving the very difficult tasks of finding tactical ballistic missiles and destroying them before, not after firing. The PDAMS concept involves ground station guidance and control of an aerial subsystem and its constituent submunitions by means of an integrated radio frequency (RF)/fiber optic data link.

TMP is a robotics system, which consists of a ground mobile, teleoperated, remotely controlled platform; a fiber optic/RF backup communication link; and, a manportable control unit. With this system, the operator can remain concealed while remotely maneuver the platform to perform reconnaissance and surveillance missions (three other papers were presented on this program and can be found elsewhere in these proceedings). With the immediate demand for new systems to evolve, developers must not attempt to do too much too soon. Such was the case with the Aquila program in which too many missions were designed into the system.

Table 1., outlines current Army programs which are active and have a draft or approved Organizational and Operational (O&O) Plan (or other requirement documents). Many programs apply to more than one mission area. This will provide significant leverage for the Government and both commercial and defense industries.

One caution to be made here is the tendency to ignore the human aspects that cannot be replaced by a robot, but which are very important to the success and survival of humans on the battlefield. For instance in the case of robotic ambulances, using a robot to transport injured soldiers is not enough. Many times what keeps a soldier alive is knowing there is another human there who is going to take care of him. Research and development must be performed with human aspects in mind. There are other requirements to consider in the development of military robotic systems, as shown in Figure 5.

Most of the robotic concepts are evolving to a family of robots: different size aerial and ground robots which are specifically designed to perform certain missions. Some of these systems will need to be expendable in the sense that they are low cost and consist of expendable technology (i.e., technology the Army can afford to lose to the enemy, if the device is captured). Vehicles with low signatures implies minimizing audio as well as visual signatures. Light weight power sources are needed for long duration missions. Data links need to be secure. Not only do they need to be jam proof, but in the case of fiber optic links they need to be robust, have low visibility, and be able to survive on the battlefield for extended periods.

Some of these requirements are beyond our current capabilities but do provide a blueprint for the future. These requirements suggest a "Hierarchy of Battlefield Robots," at least as a think piece to challenge thoughts and present perspectives of robotic applications. This Hierarchy consists of teleoperated robots, telepresent robots, semi-autonomous robots, and autonomous robots. Presently, teleoperated robots are the state-of-the-art, with telepresent robots emerging within the next 3 to 5 years. Semi-autonomous/Autonomous robots are long term efforts which will come of age over the next 10 to 15 years.

The teleoperated robot, pictorially represented in figure 6., is basically a first generation robot as far as battlefield robots are concerned, but still provides a good capability especially as an indirect fire (over-the-hill) weapon and a surveillance means. It provides a good soldier surrogate to perform high risk tasks. However, low cost, secure links and limited man-machine interface are near term technical limitations which must be overcome.

The next step is the telepresent robot represented in figure 7.; one which gives the operator some sense of "being their." This gives the operator a better capability to react to battlefield situations, such as widely varying terrain. The major technical barriers associated with telepresence are multiple sensor fusion and kinesthetic operator feedback. This class of robots will give us a reasonable tactical surrogate.

The semi-autonomous robot represented in figure 8. provides a major leap towards force multiplication. The operator becomes a manager of many robots and only needs to react to certain cues when the robot becomes confused. In fact the operator functions similar to the way a platoon leader does now. The technical barriers are not insignificant and may take as many as 10 years to solve. A Low signature is required to provide survivability. Rule generation is required to ensure the robot can react to the changing tactical situation. In many cases, these robots will be able to perform some limited platoon level functions.

The implementation of autonomous robots, illustrated in figure 9., will require a major change in Army doctrine, tactics and organization. An autonomous robot will provide a soldier surrogate capable of tactical creativity. If one stretches his imagination you can conceive of robots performing company level tasks. The technical barriers seem overwhelming in light of the change necessary to overcome the natural resistance to significant machine innovations which also cause major organizational change. There are three major technical barriers are: 1) application of artificial intelligence techniques, 2) costs, and 3) robot predictability and trustworthiness. The last may be industry's and Government's most significant task - not because of the technical barriers, but because of the cultural barriers. Developers will face a difficult tasks in convincing the soldier that he can be replaced. That instead of leading a platoon into battle, he now becomes a manager of robots. Battlefield commander's must be convinced they have absolute control of the actions taken by robots, particularly for engagement applications. However, if these barriers can be overcome, true force multiplication and soldier survivability will be achieved.

In summary, this paper has addressed a robotics progression (reference Figure 10.). Each step will provide more capability, but only after solutions to the major barriers are found. As these barriers are eliminated, robotic use on the battlefield is limited only by one's imagination and creativity. It will be possible to move from a soldier surrogate capable of performing high risk tasks, to companies of robots performing major organizational tasks.

The Government must continue to refine the Robotics Master Plan, gain acceptance of the concepts in the service, and apply the necessary resources to accomplish the Plan. Industry must apply engineering tasks associated with available and emerging technology to robotics which can make a difference on the battlefield. These applications must also have application to commercial industry if costs are to be reduced to a reasonable level. Academia must continue to advance the fundamentals of science and technology associated with the technical barriers, especially the software techniques needed to solve the artificial intelligence problem.

Hopefully, these thoughts have provided the stimulus necessary for creative minds to develop solutions to the problems surrounding this technology. The field of robotics is being used in a limited way now and the future seems bright for increased utility on the battlefield of tomorrow.

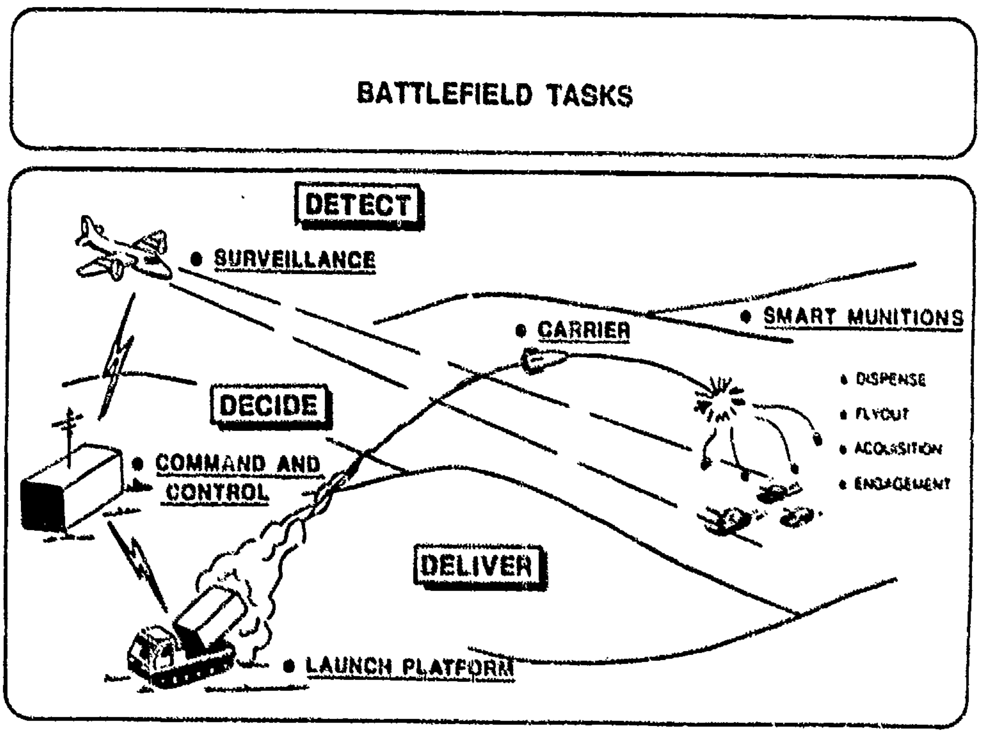

FIGURE 1. BATTLEFIELD TASKS

BATTLEFIELD ROBOTIC MISSIONS

COMBAT ARMS (INFANTRY, ARMOR, AVN, AD, FA)	COMBAT SUPPORT (ENGR, MI)	COMBAT SERVICE SUPPORT (ORD, QM, TRANS, AVN)
TGT ACQ & ENGAGEMENT	TGT ACQ & ENGAGEMENT	EOD
RECON & SURVEILLANCE	RECON & SURVEILLANCE	RESUPPLY & REARM
SECURITY	MINE/COUNTERMINE	MATERIAL HANDLING
REAR GUARD ACTIONS	NBC DECON	MEDICAL SUPPORT
FLANKING ACTIONS	TACTICAL COVER & DECEPTION	
INTERDICTION	ENGINEER SUPPORT	
MOUT		

ROBOTICS IN MANUFACTURING

TRAINING USING ARTIFICIAL INTELLIGENCE & EXPERT SYSTEMS

FIGURE 2. ROBOTIC MISSIONS

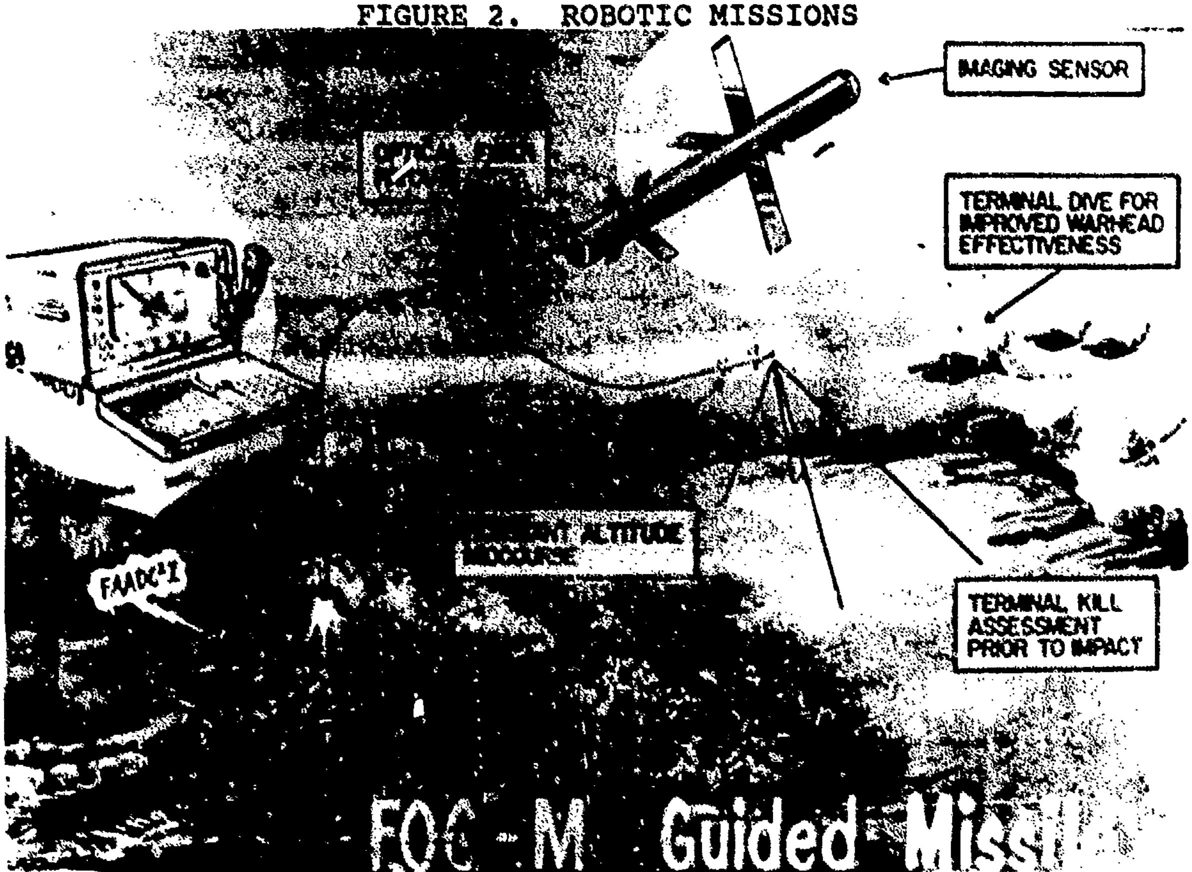

FIGURE 3. FOG-M

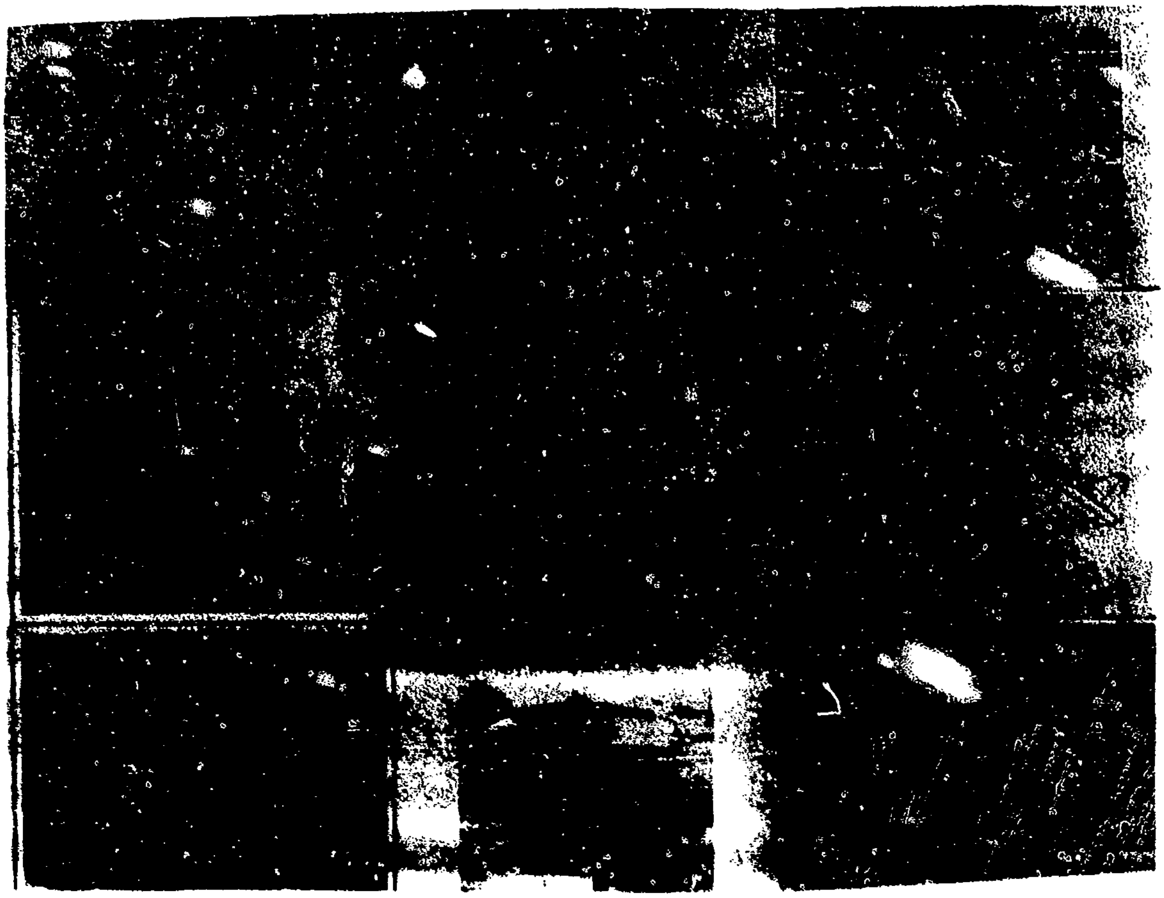

FIGURE 4. UAV

TECHNICAL REQUIREMENTS

OVERALL SYSTEM: LOW COST, LIGHTWEIGHT, EXPENDABLE HARDWARE, TRUSTWORTHINESS, SAVVY, MODULAR, ALL WEATHER, MAN-MACHINE INTERFACE, LOW OBSERVABLES

VEHICLE: ALL TERRAIN, RELIABLE, LOW SIGNATURE

POWER: EFFICIENT, NEW SOURCES

SENSORS: DAY/NIGHT CAPABILITY, ROBOTIC RELATED MULTIPLE SENSOR FUSION

WEAPONS: R&D OF WEAPONS WITHOUT HUMAN LIMITATIONS

COMMUNICATION LINK: JAM PROOF, BEYOND LOS, LONG RANGE, SECURE NONMATERIAL[illegible]M

NAVIGATION: INEXPENSIVE, RELIABLE, INTEGRATED W/C3I AND GPS FOR ROUTE CONTROL

CONTROL UNIT/STATION: OPERATOR CUEING, MULTIPLE VIEWS, MULTIPLE CONTROL, LOW POWER CONSUMPTION

FIGURE 5. TECHNICAL REQUIREMENTS

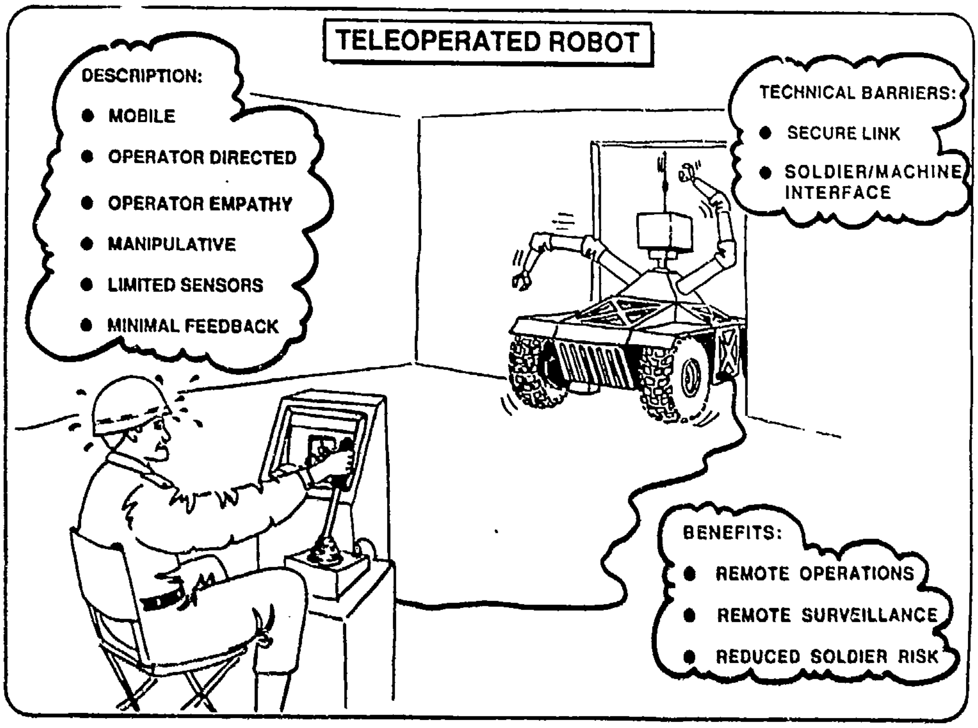

FIGURE 6. TELEOPERATED ROBOT

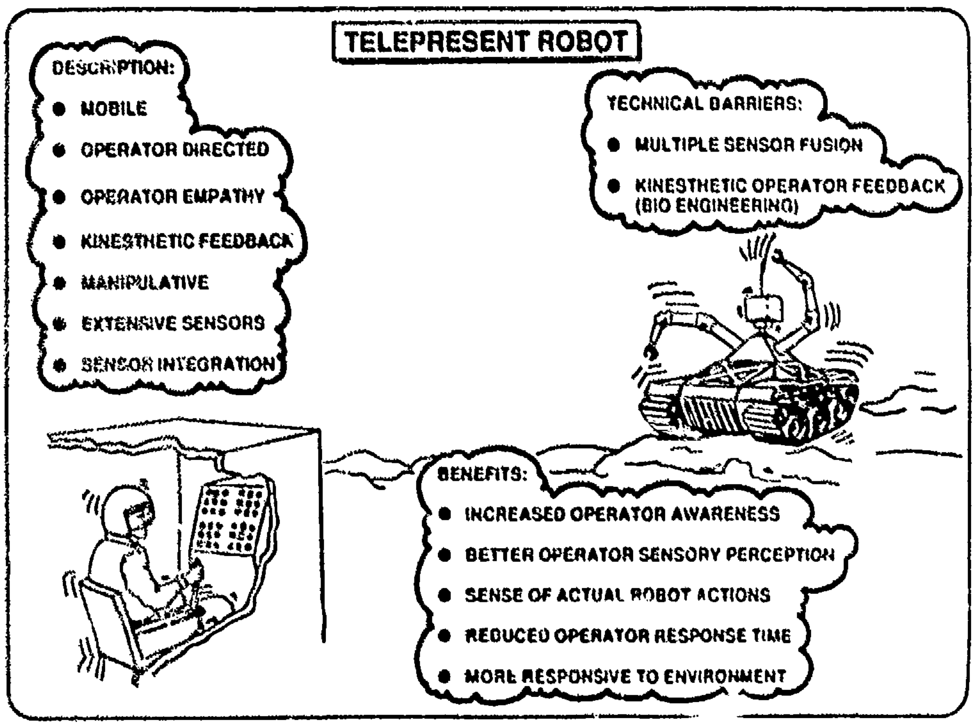

FIGURE 7. TELEPRESENT ROBOT

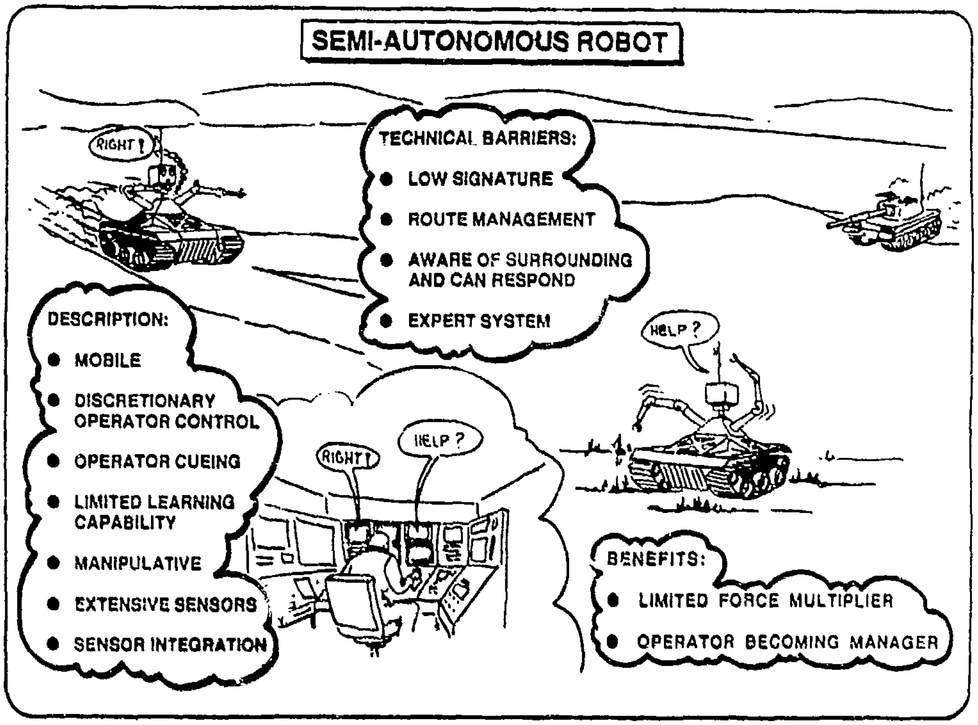

FIGURE 8. SEMI-AUTONOMOUS ROBOT

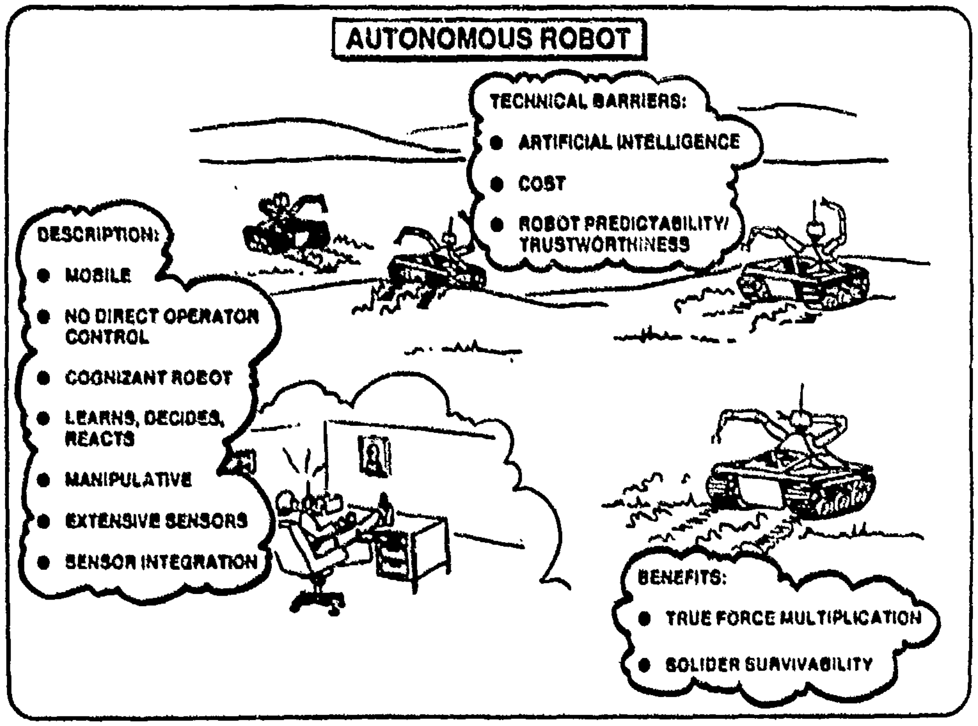

FIGURE 9. AUTONOMOUS ROBOT

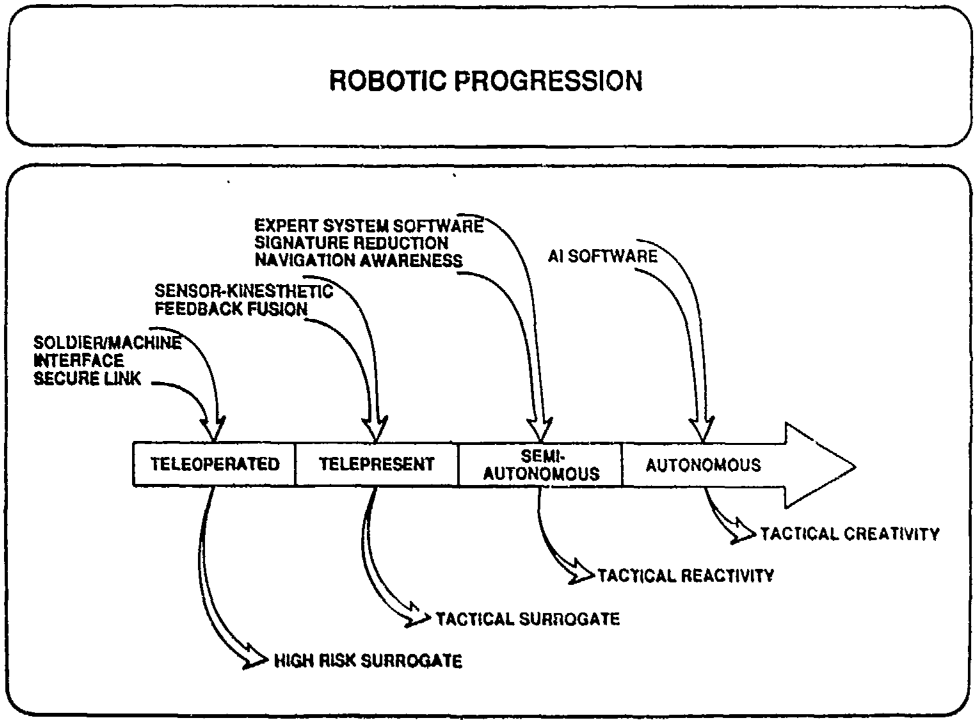

FIGURE 10. ROBOTIC PROGRESSION

ROBOTIC MISSIONS/PROGRAMS MATRIX

MISSIONS	COMBAT ARMS	COMBAT SUPPORT	COMBAT SERVICE SUPPORT
RECONNAISSANCE	TMP, UAV, RCV	UAV	N/A
SURVEILLANCE	TMP, UAV, RCV	UAV	N/A
ANTIAIR	FOG-M, SMART WEAPONS		N/A
ANTIARMOR	TMP, UAV, FOG-M, PDAMS SMART WEAPONS, RCV	N/A	N/A
ANTIPERSONNEL	TMP, AFAS		N/A
PARTICULAR TARGETS	FOG-M	PDAMS	N/A
FORWARD OBSERVER	TMP, UAV	TMP, UAV	N/A
SENTRY/OUTER PERIMETER	TMP, RSSS	TMP	N/A
MINE DETECTION/CLEARING/EOD	RONO, RCRM	RONO, RCRM	RONO, RCRM
TARGET DESIGNATOR	TMP, UAV	TMP, UAV	N/A
AMBUSH	TMP, RCV	N/A	N/A
DECOY		TMP, UAV	N/A
AMBULANCE/MEDIC SUPPORT	TMP	N/A	(AMBULANCE/MEDIC ROBOT)
SUPPLY DELIVERY/SHUTTLE	TMP	N/A	USOCH, UAV

TABLE 1. ROBOTIC MISSIONS/PROGRAMS MATRIX

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21-22 June 1988 GACIAC PR 88-02

TMAP - THE ARMY'S NEAR TERM ENTREE TO BATTLEFIELD ROBOTICS

May 1988

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Baltimore, Maryland

ABSTRACT

TMAP is a remotely operated battlefield system consisting of a 750-pound all terrain vehicle, remotely operated by a soldier over a fiber optic communication link 4 km long. Using state-of-the-art automation and robotic technology, Martin Marietta Aero & Naval Systems is developing a modular prototype system under contract to Sandia National Laboratories. The Army Materiel Developer is the Missile Command (MICOM) at Huntsville, Alabama; the Combat Developer is the Infantry School (USAIS) at Ft. Benning, Georgia. With the weapons removed by Congress in December 1987, the O & O is being rewritten for a "Tactical Multipurpose Automated Platform" (TMAP) instead of the original Teleoperated Mobile Antiarmor Platform. With minimal modification, the modular TMAP system can be used in many applications (e.g., antiarmor or antiair weapons, mine detection, medical support). System acceptance testing and Army evaluation testing are scheduled for summer and fall of 1988.

1.0 INTRODUCTION

TMAP was conceived by the Army in 1985 as an approach for utilizing state-of-the-art automation technology to protect humans from the hazardous battlefield environment while allowing them to maintain control of weapons (see Figure 1). This excellent idea evolved into two industry contracts to develop prototype systems for evaluation.

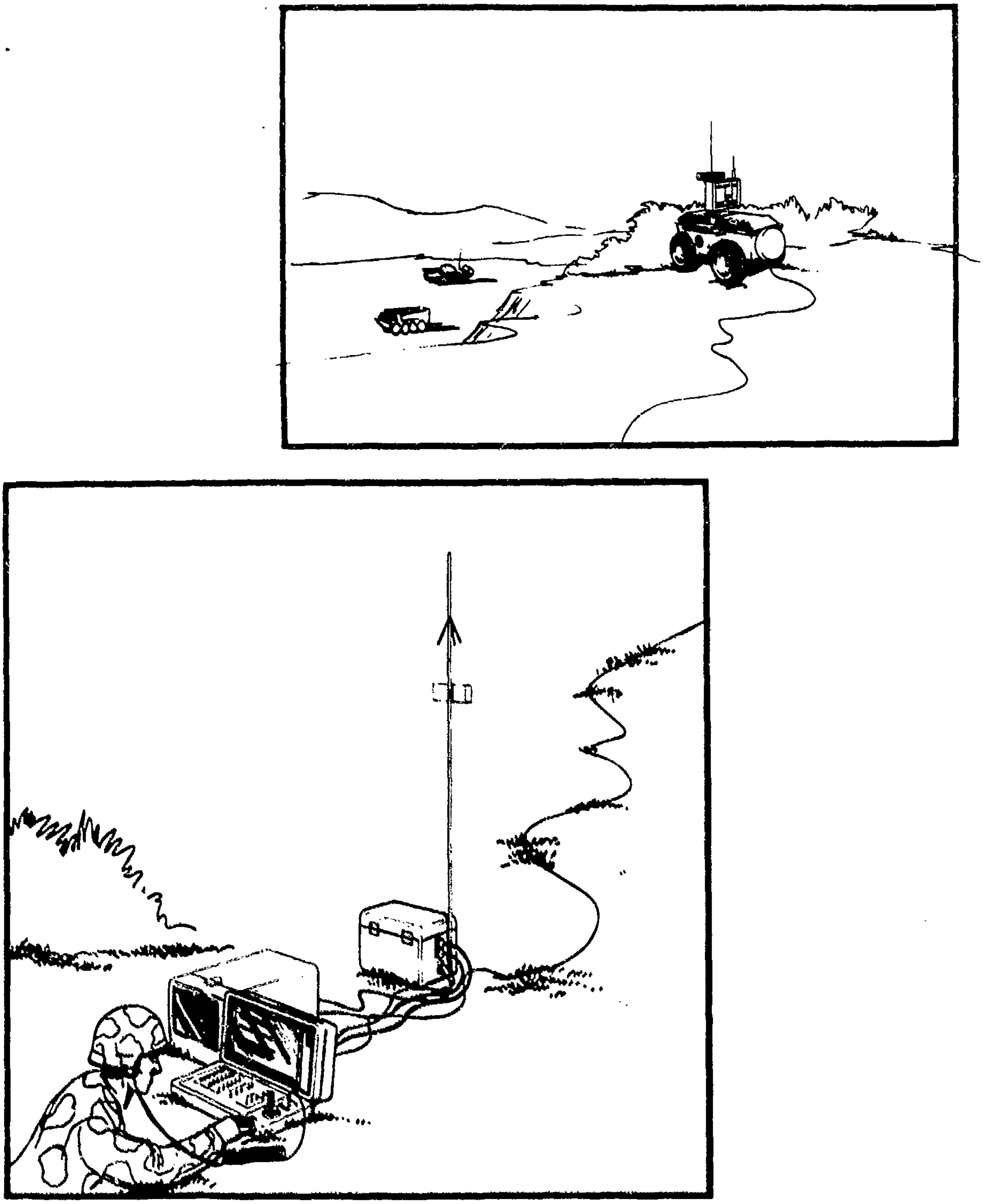

FIGURE 1: THE WEAPON SYSTEM OPERATOR IS REMOVED FROM HIGHLY LETHAL ENVIRONMENTS USING ROBOTICS TECHNOLOGY

The original idea incorporated weapons and sensors to determine if an effective, remotely operated antiarmor weapon and surveillance system could be developed using a small, all-terrain vehicle.

The Teleoperated Mobile Antiarmor Platform (TMAP) was well along in development in December 1987 when the language in the FY 1988 appropriations bill removed the weapons from the platform. The Infantry School initiated a new requirements document, the O & O plan, calling for development of a "Tactical Multipurpose Automated Platform." This change was easily accomplished by Martin Marietta and the resulting state-of-the-art, remotely operated, automatic modular system with a laser designator as its first modular payload will be acceptance tested in August 1988. In May 1988, Martin Marietta was awarded a test support contract for training, test equipment, and spares to support the Army's TMAP evaluation testing at Ft. Benning in the fall of 1988.

This development program has adapted many existing components and advanced the state of the art in other areas to provide a very capable, flexible, and evolvable system for Army evaluation. It will be a useful tool for determining the utility of automation and robotic technology in redressing the balance of forces, which currently favors the Soviets. The system described in this paper is readily adaptable to a variety of missions, including the original anitarmor mission.

2.0 TMAP PROGRAM

In July 1987, Martin Marietta Aero & Naval Systems received a $2.65 million, 14-month contract to develop a prototype Teleoperated Mobile Antiarmor Platform. The contract came from Sandia National Laboratories in Albuquerque, New Mexico, with Dr. James Kelsey as Program Manager. The Materiel Developer is the Army Missile Command (MICOM) in Huntsville, Alabama, under the direction of Dr. Johnny Prater. The Combat Developer is the Infantry School (USAIS) at Ft. Benning, Georgia.

In the original concept, TMAP included an all-terrain vehicle with antiarmor weapons, cameras, and other sensors remotely controlled by an infantryman over a fiber optic link. The soldier would detect and identify enemy armored vehicles and engage in direct fire with them while remaining completely hidden.

The objectives of this prototype program were to (1) develop, design, and fabricate the smallest, lowest cost, lowest weight TMAP system possible which would effectively demonstrate an antiarmor capability, (2) reduce technical risks to an acceptable level for entering Full Scale Development (FSD), and (3) provide adequate supporting data for cost and operational effectiveness assessment prior to the FSD decision. In addition, the TMAP prototype was intended to be a tool to support O & O and ROC development.

Specific goals of the current program are to provide a system that is simple to operate and maintain, reduces force structure demands, is safe and hazard free, and can be field demonstrated to prove its utility. Components not in the military system are acceptable, but MIL SPEC equipment is to be used wherever possible.

Mission capability was to include typical infantry antiarmor and scout missions with future supplementary capability for NBC surveys, listening post/outpost (LP/OP), artillery forward observer/designator, and battle damage assessment.

The technical requirements defined a listening mode in which platform noise was not to be detectable at 50 meters against a background noise level of 20 dB (10 dB desired). The platform was to be capable of remaining in this mode for 12 hours (72 hours desired). The overall vehicle weight was not to exceed 370 kg; the operator control unit (OCU) was not to exceed 16 kg; and the OCU power supply was not to exceed 16 kg.

3.0 TMAP SYSTEM

TMAP is composed of the platform, a man-portable operator control unit (OCU), and the OCU power supply. These are shown in Figure 2. The vehicle is shown configured with the Laser Designator mission module.

The primary communication link is fiber optics (FO). A 4-km FO cable, played out as the vehicle travels, connects the platform with the OCU. A backup radio frequency (RF) link is also provided.

In a TMAP mission in which the operator selects a site from which to operate and then drives the platform to a remote location, the key elements of operation include: receiving the mission requirements, planning the mission

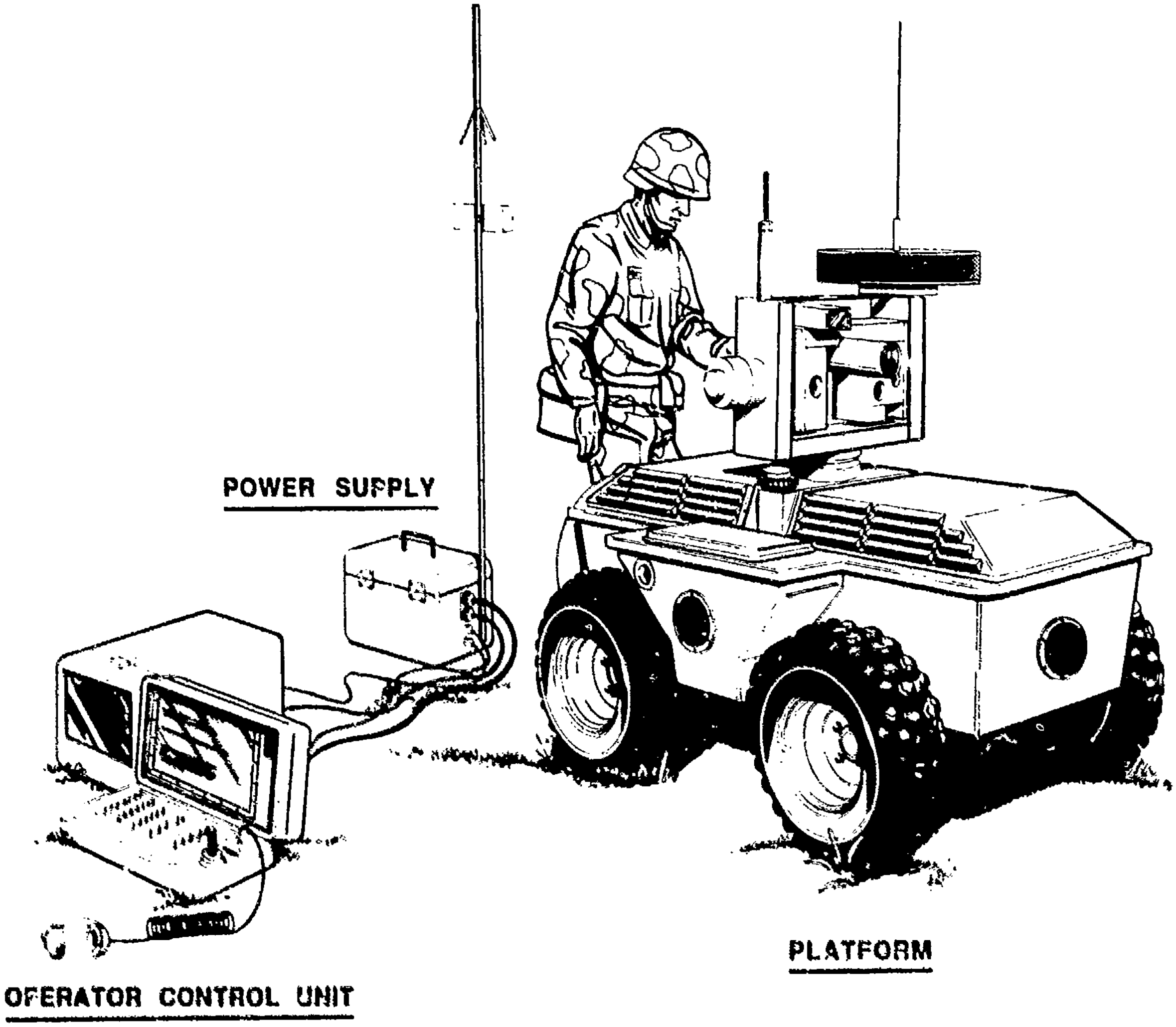

FIGURE 2: THE TMAP SYSTEM

and the route, setting up the platform and the OCU, driving and navigating the platform from the known point with navigation updates, positioning the platform for mission accomplishment, and returning the platform to the starting point.

The OCU and OCU power supply are set up as shown in Figure 2. Then, using the target camera and laser range finder, the operator obtains range and bearing to several landmarks from the vehicle's initial position. This information is entered into memory. Several key positions (way points) along the planned route are also entered using military map coordinates, and these data (initial position and way points) are displayed on the OCU's liquid crystal display.

The platform is driven along the planned route using the driving camera display on the CRT monitor. In this mode, the operator sees a cue on the video monitor that shows him the direction he should be moving to reach the next way point. The platform's line of travel is also continuously updated by the on-board dead reckoning navigation system and displayed on the LCD. Periodically, the operator stops the platform and gets an accurate position update by re-sighting the landmarks previously located. A display of the expected bearing and distance to the landmarks from the platform's new position helps the operator find the landmarks. The operator also takes sightings on new landmarks further along his route. This procedure augments the dead reckoning system to provide the required navigational accuracy.

For a reconnaissance mission, the route would be in rosette pattern and the platform would end up back at its starting position. If an overwatch is to be established, the platform is driven to the desired location and positioned. An initial visual surveillance is then made using both driving and sighting cameras. For long-term surveillance, the system is put into its low-power, listening mode using the acoustic system for automatic warning (alert), allowing the operator to eat, sleep, or perform other duties.

In the listening mode, the acoustic system continuously monitors and will warn the operator of the presence of personnel or vehicles. With such a warning, the operator can obtain further acoustic identification and location information using the headphones before he powers up the system to visually survey the area. If enemy vehicles are in view he can sight on them with the sighting/aiming camera (day or night) and target them with the laser designator. In the original weapon-mounted configuration he would track the target (either manually or automatically), range with the ranging laser, and after a firing solution has been computed, fire the antiarmor weapon.

Returning the platform to the rear area can be done using the fiber optic communications link or the backup radio frequency link.

The following paragraphs describe the system elements. Commercially available components are used where cost and schedule could be met only by using them. New developments and available hardware are used together to provide a very capable, flexible, and modular system that meets Army TMAP specifications and provides for growth to include a variety of future payloads.

3.1 PLATFORM

The platform shown in Figure 3 includes the mobility base unit; the modular mission head (formerly the weapons head); the sensor suite; the land navigation unit; the video auto tracker; the communications links; and the navigation, processing, and control electronics. The platform is 66 inches long, 48 inches wide, and 50 inches high to the top of the mission head. It weighs less than 370 kg and can travel at up to 15 km/hr. It has excellent mobility in rough terrain and on steep slopes.

Mobility Base Unit

The mobility base unit (MBU) is a 4-wheel, diesel powered, hydraulically driven, skid steered, all-terrain vehicle developed by Deere and Company. The body is a fiberglass layup.

The four wheel motors are driven by two hydraulic pumps powered by a 6-horsepower diesel engine.

Most of the electronics are packaged in an environmental enclosure in the rear vehicle compartment. Other components are located in the saddlebags. The pendant for moving the MBU without using the OCU is located in the right saddlebag.

The turret that supports the modular mission head (MMH) is located in the center of the vehicle. The azimuth drive motor is part of the turret assembly.

The fiber optic cable dispenser, mounted on the MBU rear surface, carries and dispenses 4 km of FO cable. The cable winding is lemniscate, which provides the simplest, most reliable method of cable dispensing and simplifies

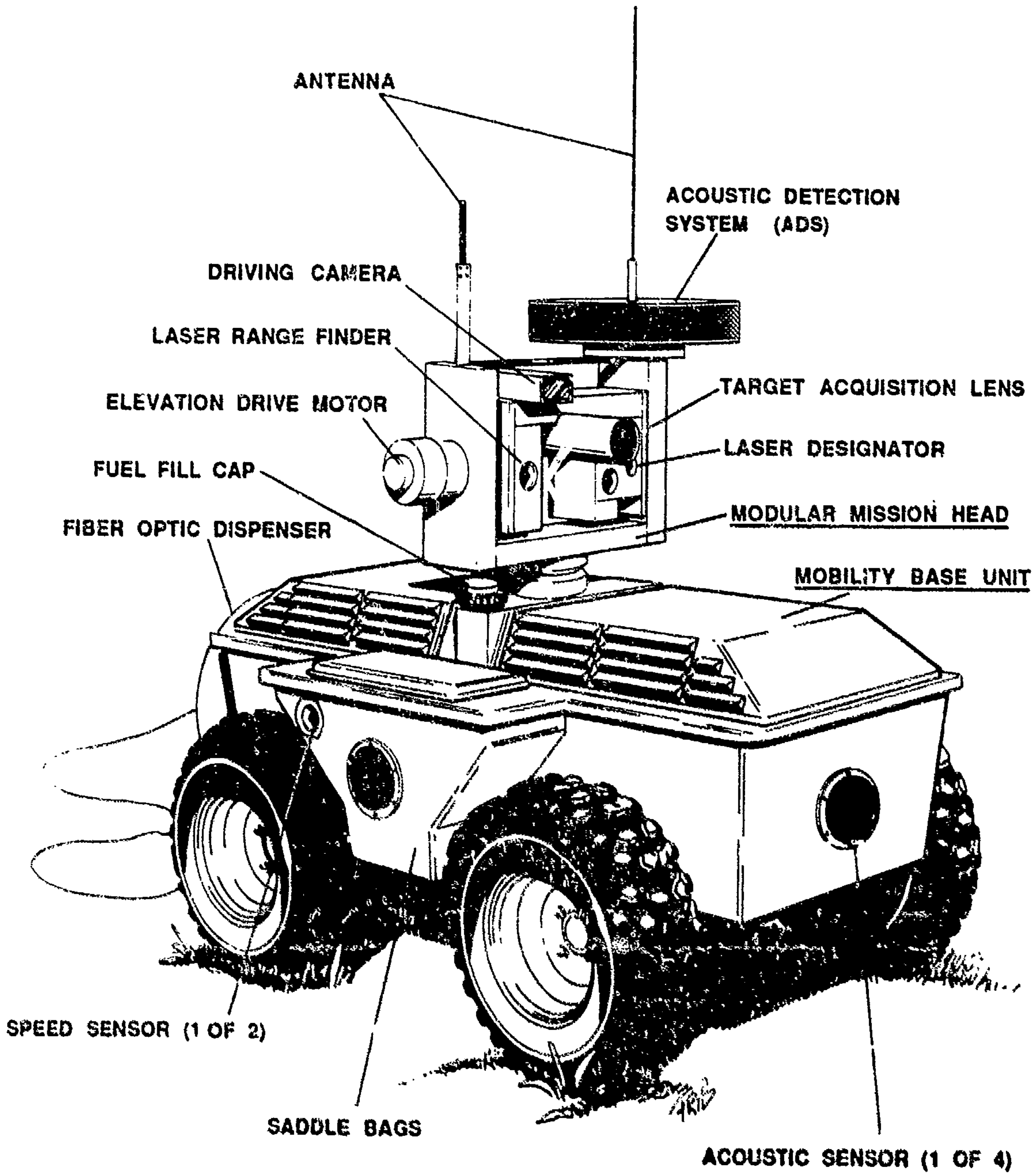

FIGURE 3: TMAP PLATFORM

rewinding. This technology eliminates cable twist during playout and significantly reduces the probability of breaks due to kinking.

Sealed lead-acid batteries are located in the lower section of each saddlebag. Batteries are recharged by the diesel engine alternator.

Modular Mission Head

The modular mission head (MMH) includes the structure that mounts many of the mission sensors along with the RF antennas. The head is driven plus or minus 270 degrees in azimuth and plus 35 degrees and minus 15 degrees in elevation. Antennas and acoustic sensors are mounted on the structure that is driven only in azimuth.

Sensor Suite

The primary sensors in the sensor suite include the driving camera, targeting and night vision camera, laser range finder, and laser designator (all mounted in the MMH elevation structure), the acoustic detection system mounted on the azimuth-driven MMH structure, and the body-mounted sensors which include the four acoustic sensors and two speed sensors. Other sensors mounted internally include the heading sensor, inclinometers, 3-axis accelerometer, fuel level and oil pressure sensors, engine speed indicator, wheel encoders, battery charge level sensor, and temperature sensors of engine, electronics, hydraulic pump, and batteries.

The driving camera is a fixed-focus, color, CCD camera with a 52-degree field of view, auto-iris lens. The targeting and night vision camera provides both day and night vision. The targeting lens can be zoomed from 25 mm to 350 mm providing a 14 to 1 magnification. The original range requirement for the antiarmor configuration was 500 meters. This has been extended with the zoom lens now in the system to an identification range well beyond 1000 meters. This camera subsystem, at its lowest magnification, provides a 20 degree field of view for night driving.

The laser range finder is an eye-safe, gallium arsenide laser with a range well beyond 500 meters. It provides range to target when the firing switch is activated. This information is automatically entered into a tracking solution or is used for navigation position update, depending on the operating mode.

The modular payload, laser designator is a yag laser, not eye-safe, that provides a single designation mode at this time.

The RF antennas include the 407.6 megahertz command receiving antenna and the 1743 megahertz video transmitting antenna.

The acoustic sensors are mounted on top of the MMH and on the front, sides, and rear surfaces of the MBU. The acoustic sensor system provides three functions: 1) alert of potential target along with an approximate azimuth to the target, 2) alert of live object movements and the capability for the operator to use headphones to determine if the alert is a human source, and the azimuth to the source, and 3) identification and tracking of tracked or wheeled vehicles. Detection range of vehicles is compatible with current antiarmor weapons.

Two speed sensors are mounted on the body to sense forward, backward, and side mot'... The output of these ultrasonic sensors is used in the navigation computations.

The solid state heading sensor subsystem consists of a fluxgate magnetometer coupled to a yaw rate sensor. Magnetic heading from this sensor is used in the navigation computations.

Vehicle fore and aft and side to side inclination and inclination rate are provided by the two-axis inclinometer. These data are used in three ways: 1) in navigation computations to determine vertical motion, 2) in target location and tracking to allow for MBU deviation from horizontal position, and 3) to warn the operator of imminent vehicle turnover from operating on too steep slopes.

Wheel encoders provide vehicle motion direction and speed to the control electronics to provide smooth, responsive control of vehicle motion. These data are also used in conjunction with the ultrasonic speed sensor data in navigation computations.

Fuel level, oil pressure, engine speed, and battery charge status data are sensed and shown graphically to the operator.

Land Navigation Unit

Land navigation data are provided by a combination of the sensors described in the preceding paragraphs. These include the targeting camera and laser range finder for triangulating vehicle position, and the ultrasonic speed sensors, magnetic heading sensor, inclinometers, and wheel encoders.

Platform position and track are calculated within the navigation, processing, and control electronics (NPCE) using a dead reckoning method, and displayed to the operator along with heading and platform velocity on the liquid crystal display in the OCU.

Another feature of navigation provided by the OCU portion of the NPCE is the ability to enter and graphically display, on the OCU liquid crystal display, waypoints of a planned route within the local military map coordinate system.

Video Auto Tracker

The video auto tracker (VAT) automatically tracks targets that are identified using the box-shaped tracking cursor displayed on the OCU video monitor in the tracking mode. Once set, the cursor follows the target, and can drive the turret assembly to keep the targeting camera and payload module pointed at the target. A tracking solution can also be obtained by manually tracking a target and entering two target positions into the computer. The system projects a path and automatically tracks the target.

Communications

Two communication links are provided. The primary link is a 4-km fiber optic cable which provides secure communication of commands, status, and video data between the platform and the OCU. The FO system also includes the cable dispenser previously described.

A backup radio frequency (RF) system is available to the operator if the FO system fails. Both command and video data are provided by the RF system. Two RF frequencies are used, 407.6 megahertz for the command link and 1743 megahertz for the video. Status and audio data are transmitted over the video link. Total system capability exists using either communication link.

Navigation, Processing, and Control

The software/hardware control system is the heart and major subsystem of the Martin Marietta TMAP system. The simple platform system block diagram in Figure 4 shows the interfaces between the previously discussed system elements and the navigation, processing, and control electronics.

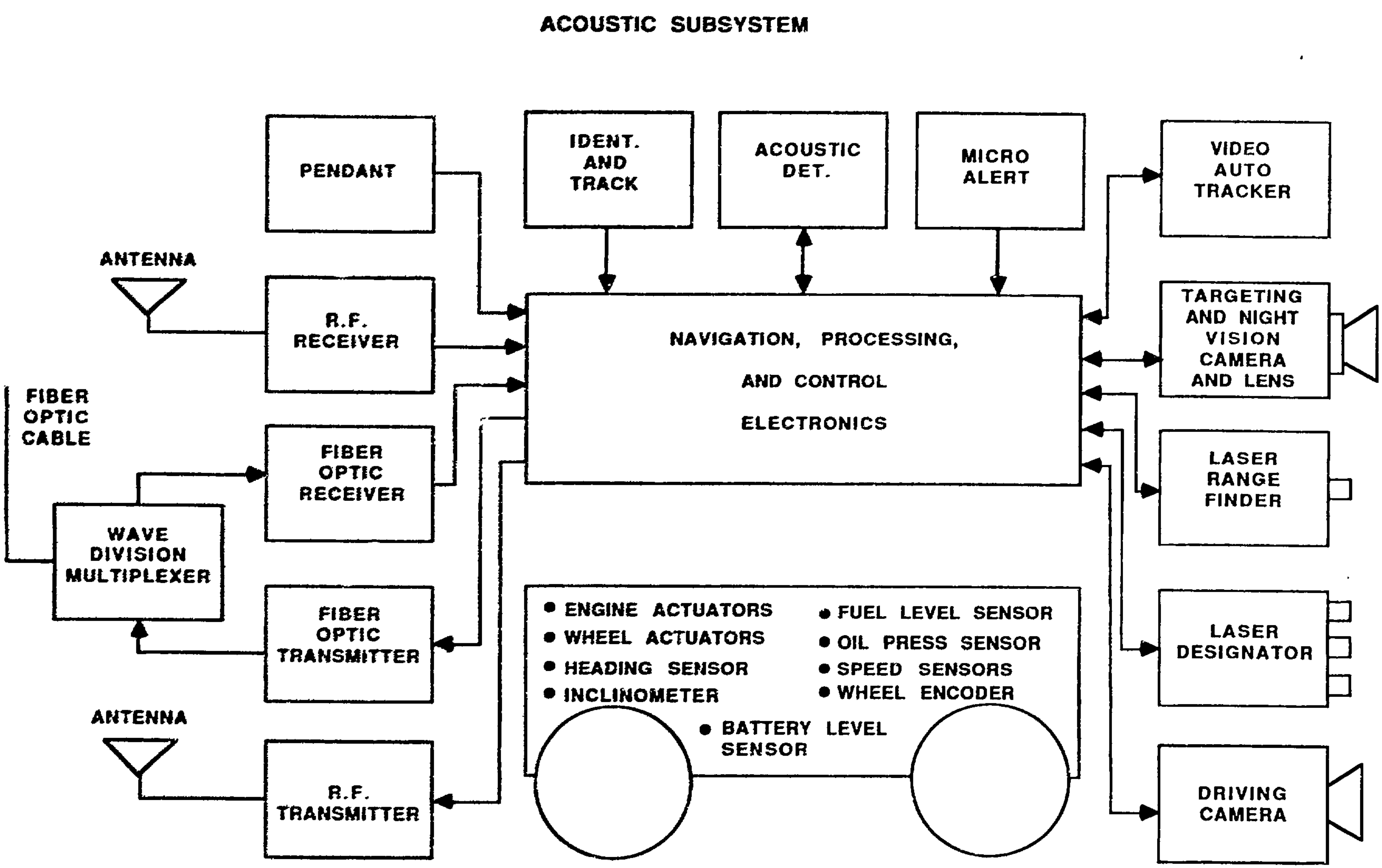

FIGURE 4: TMAP PLATFORM BLOCK DIAGRAM

The system software/hardware design incorporates a state-of-the-art approach to process control and data management for remote vehicle operations. The real time control system (RCS) architecture selected is an evolution of the hierarchical control technology that began in the National Bureau of Standards over 14 years ago. This approach, refined at Martin Marietta over the past 2 years by two of the original codevelopers (Dr. Tony Barbera and M.L. Fitzgerald), uses multiprocessors on a common bus architecture to ensure extremely rapid cycle times while allowing for growth. This same architecture is being standardized for use by NASA in their Space Station Telerobotic System.

Table 1 describes the basic function of each of the control levels; Figure 5 is a block diagram of the top level of the control system. Table 1 and Figure 5 also show the six CPUs used in the system (five in the vehicle and one in the OCU).

3.2 OPERATOR CONTROL UNIT (OCU) AND POWER SUPPLY

The man-portable OCU and power supply are shown in Figure 6. The system consists of two units, each weighing less than 16 kg. Packaged for carrying, the OCU is 14 inches long, 10 inches wide, and 17 inches high. The power supply is 13 inches long, 9 inches wide, and 11 inches high.

Operator Control Unit

The OCU includes two separable elements, the video monitor and the controls and electronics assembly. Included in this assembly are the video monitor, liquid crystal display, control panel, and LCD graphics, processing, and control electronics (LGPCE). The 9-inch color monitor is housed in a case that includes a front cover with window. The controls and electronics assembly is a hinged box that opens up as seen in Figure 6 to provide access to the control panel and the liquid crystal display. The opened assembly attaches to either side of the video monitor for stability and to allow for both right- and left-handed operators. Interconnecting cables and headphones are carried in the back of the monitor enclosure.

All TMAP system functions are controlled from the control panel. The liquid crystal display shows navigation and target location and tracking

TABLE 1
CONTROL LEVEL DESCRIPTIONS

System Control Level: Controls the operation of the entire system. Determines if TMAP is running in training mode or regular operating mode. CPU 1.

Mission Control Level: Does the major decision processing required to sequence the system through each of its major missions. Determines the major operating modes, e.g., Mobility, Navset, etc. CPU 1.

Platform Control Level: Controls the operator's high level identification and surveillance capabilities. Controls the functions of the acoustic sensor system and the cameras. CPU 1.

Subsystem Control Level: Directs the operator's joystick inputs for the control of the turret or the vehicle. Coordinates the laser ranger and autotracker information to provide turret positioning commands. CPU 2.

Vehicle Control Level: Determines the state of the engine and determines the next commanded wheel speed based on the present speed and direction of the vehicle with respect to ground. CPU 3.

Wheel Speed Control Level: Given a wheel speed as an input command, this level determines what position to set the swash plates to achieve this wheel speed based on vehicle load parameters. CPU 3.

Actuator Position Servo Control Level: Determines what voltage to put to each of the motors to null the position error. CPU 3.

Turret Control Level: Given a pointing vector, determines the postion/rate values and servo parameters to send to the motion controller board. CPU 2.

Platform Operator Control Level: Interprets requests from the pendant or data received over the communications link from the OCU to make the inputs from the operator available to the running control system and initiate generation of appropriate status displays. CPU 4.

Data Control Level: Provides an interface into the World Model Data Base from the running Platform Control System to gather the data required to generate the requested status displays, and to maintain data in disk data files. CPU 4.

Graphics/LCD Screen Control Level: Given a request for a status display for either graphics overlay or the LCD, configures icons and screen locations and sets up the sequence of command primitives for the devices. CPU 5.

Graphics/LCD Display Control Level: Sends out primitive operation requests to the device controller boards. OCU CPU.

Disk Data File Control Level: Controls data on the disk, doing retrieval and storage when commanded. CPU 5.

Communications Control Level: Controls the transmission and receiving of data packets through the Fiber-optic or RF communication link, handling checksum generation and packet sequencing. CPU 4.

Operator Control Level: Provides the high level interface to the operator that determines the system operating mode. OCU CPU.

Option Control Level: Based on the present mode of the system, collects the operator input data from the panel, interprets it, issues commands to generate LCD displays is necessary, packetizes the data to be sent to the platform and sets OCU status LEDs. OCU CPU.

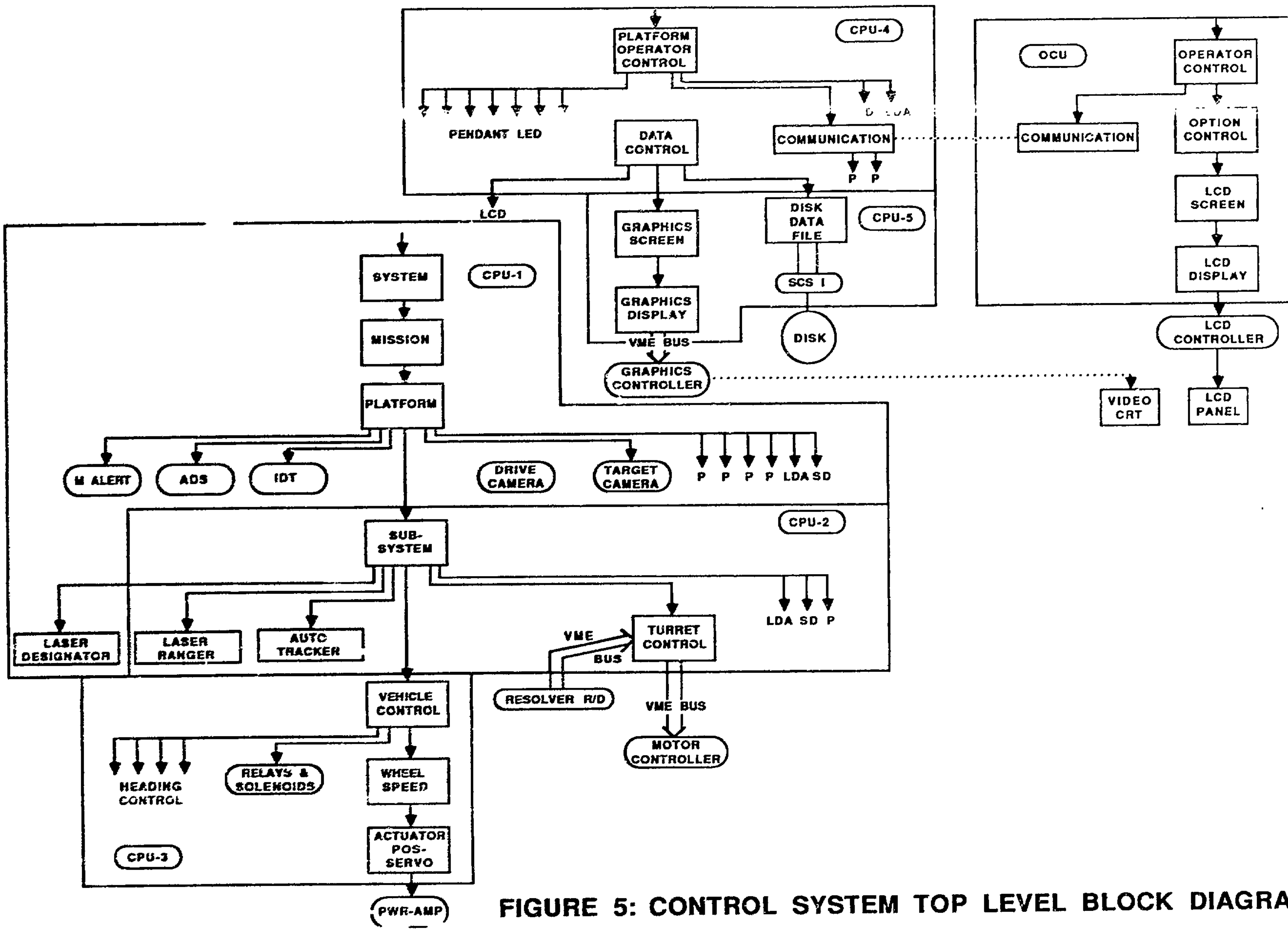

FIGURE 5: CONTROL SYSTEM TOP LEVEL BLOCK DIAGRAM

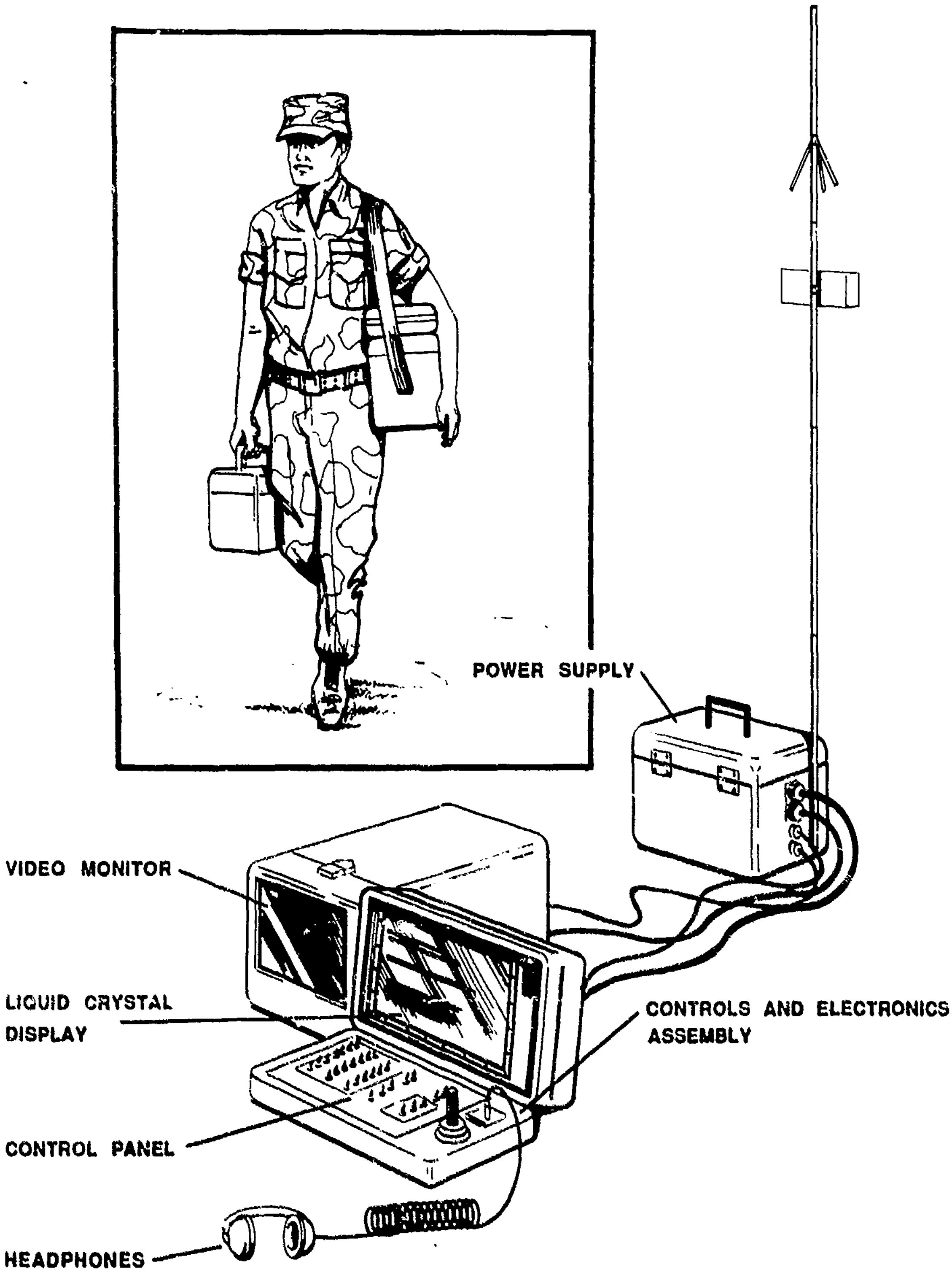

FIGURE 6: OPERATOR CONTROL UNIT AND POWER SUPPLY

information in military map coordinates. Graphics for the target, vehicle, and landmark positions and for vehicle position tracking are generated within the LGPCE subassembly.

OCU Power Supply

The OCU power supply includes batteries and communications hardware. The RF antenna package is also part of this assembly. Mission batteries are high-energy-density primary lithium batteries. These provide the required 12-hour mission within the 16 kg weight limitation. Rechargeable, sealed lead-acid batteries can be used for development, training, and testing.

The communications housed in the power supply enclosure include FO and RF transmitters and receivers, and the FO wave division multiplexer. The RF antennas are separately packaged.

Figure 7 is a simplified OCU block diagram.

3.3 SYSTEM POWER REQUIREMENTS

System power requirements for the listening mode and active surveillance mode are shown in Table 2 as a function of the communication system being used.

TABLE 2

SYSTEM POWER REQUIREMENTS IN WATTS

	Listening Mode		Active Surveillance Mode	
	RF	FO	RF	FO
OCU	20	15	45	50
Platform	95	50	200-350	150-300

4.0 TMAP ALTERNATE CONFIGURATIONS

The TMAP system, as designed, can easily be adapted to a number of combat, combat support, and combat service support missions. The flexible, evolvable MBU and OCU software/hardware control system can be extended to include additional or alternate weapons and sensors. The turret and body

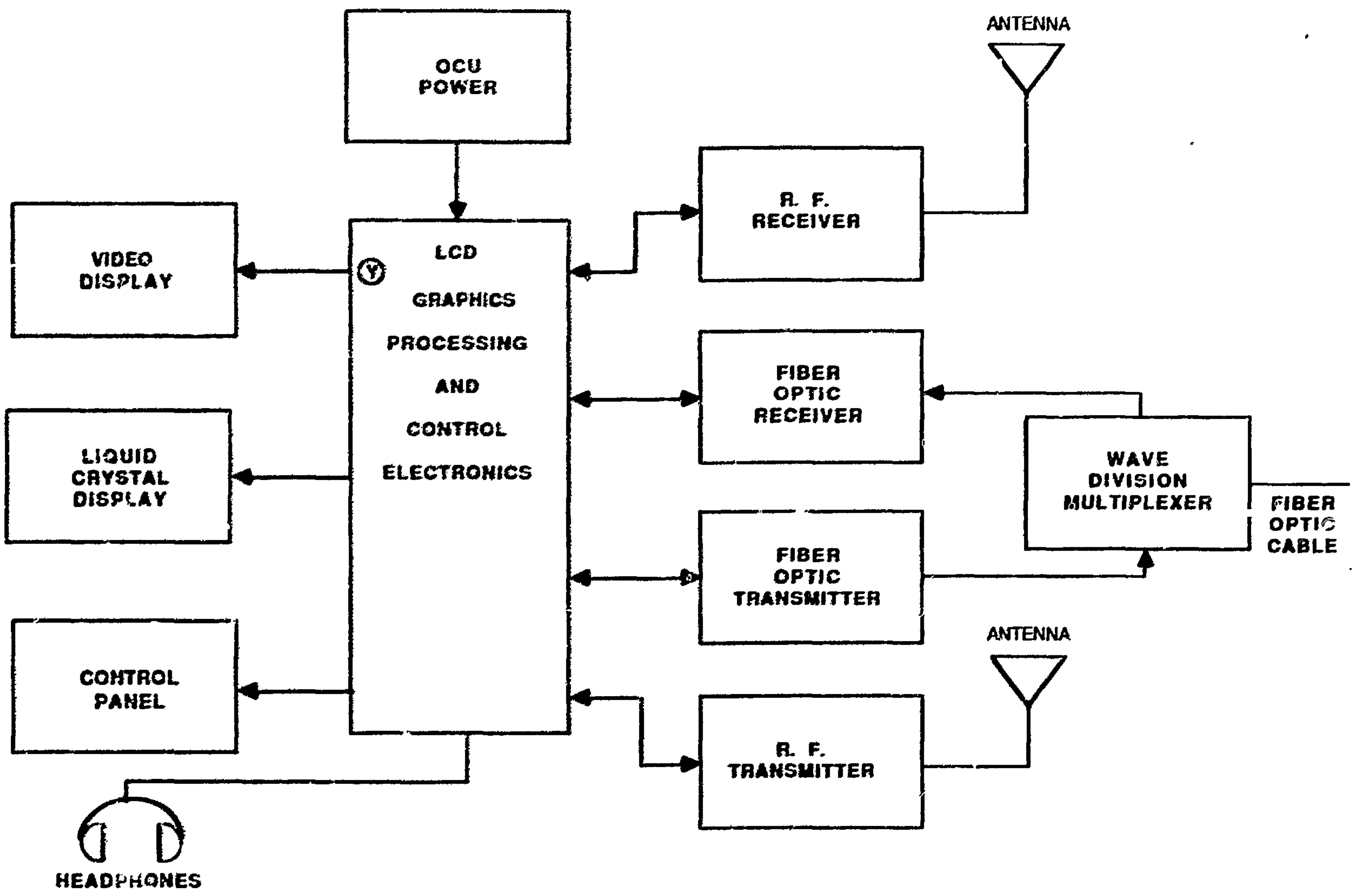

FIGURE 7: OCU BLOCK DIAGRAM

upper structure can be designed to carry a variety of weapons and sensors. The basic OCU and its power supply and the mobility base unit without mission module are shown in Figure 8.

With little modification the system can carry the original payload of two or three AT-4 antiarmor weapons and self protection weapons (see Figure 9). Concepts for other weapon payloads include AAWS-M, TOW, and Stingers. Other uses include mine detection, NBC detection, medic support and equipment carrying.

The well-integrated processing and control system, communications, auto tracker and sensors could also be used in other vehicles without modification other than mounting and cabling. The operator control unit and power supply can be used in this regard with no changes.

TMAP with its varied payload capability can be a major factor in redressing the current balance of forces, which currently favors the Soviets. Two important advantages are afforded by robotics technology.(1) First, with fiber optic links and teleoperation concepts, the number of weapon systems controlled by Allied combat units can be increased without increasing unit size. Second, robotics would remove the weapon system operator from highly lethal environments, and thus increase the survivability of highly trained and experienced US weapon crews.

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(1) Carlucci, Frank C., Secretary of Defense, "Soviet Military Power - An Assessment of Threat - 1988", p. 154.

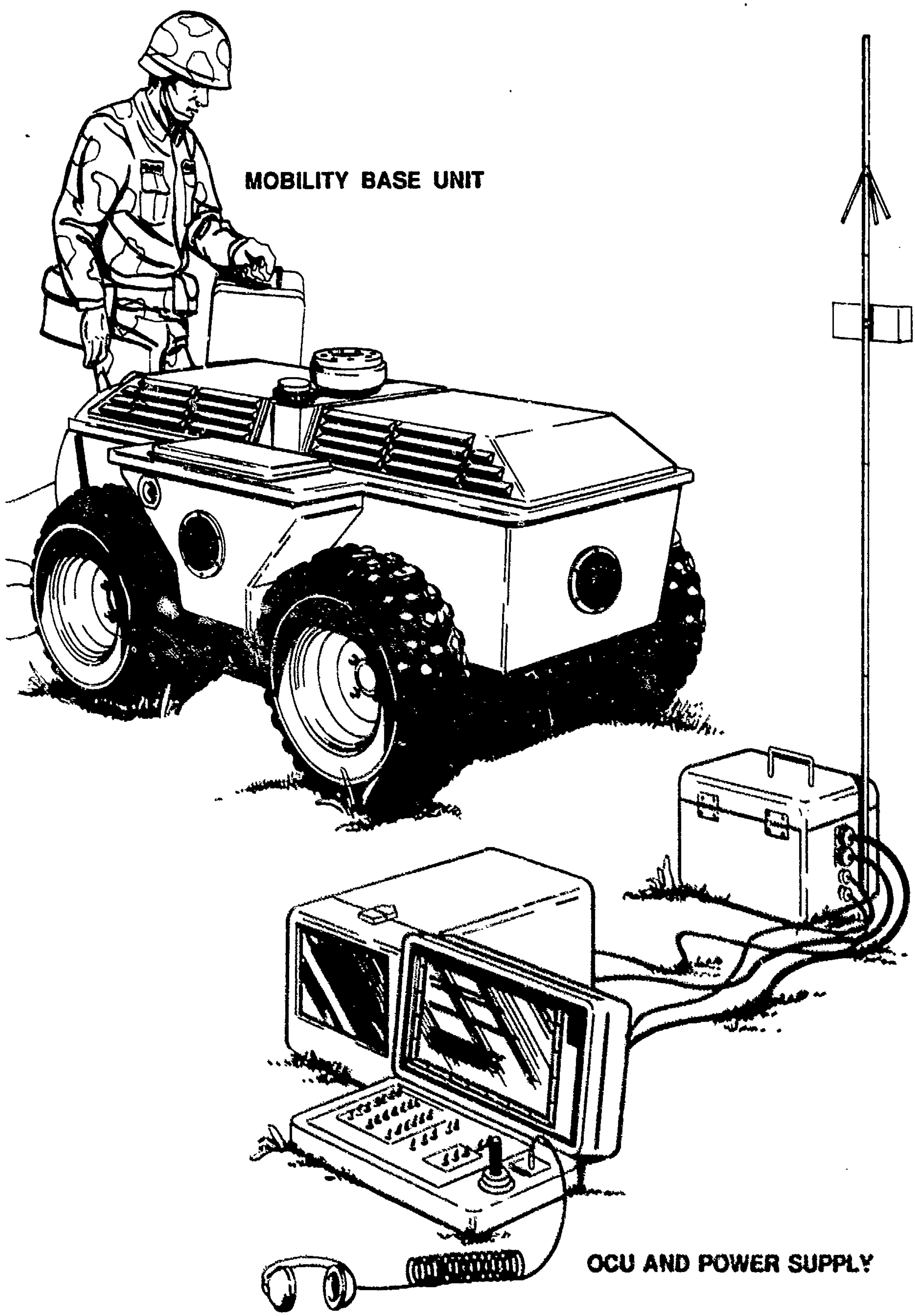

FIGURE 8: THE BASIC TMAP SYSTEM ELEMENTS CAN BE READILY ADAPTED TO A VARIETY OF MISSIONS

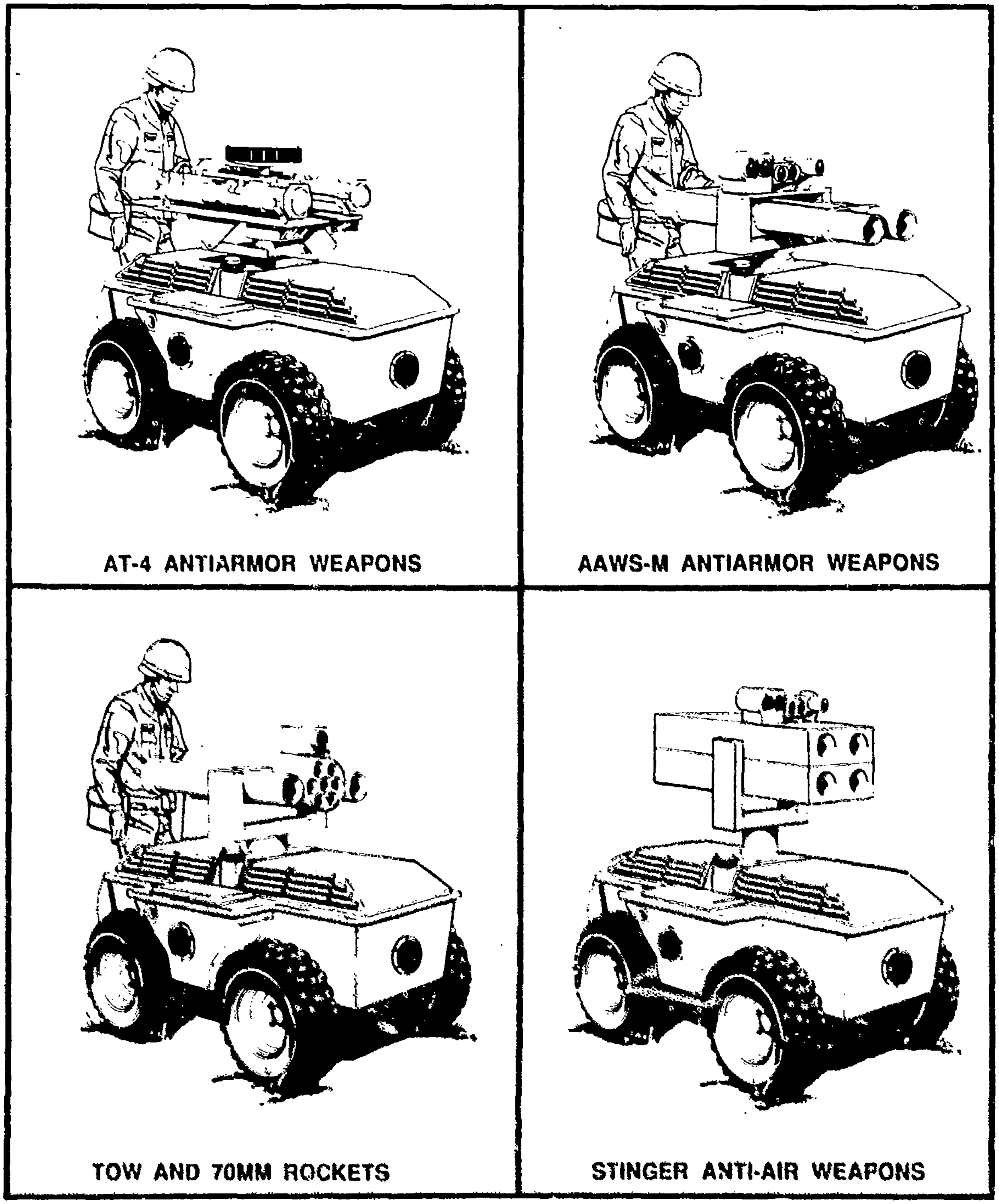

FIGURE 9: TMAP ALTERNATE CONFIGURATIONS

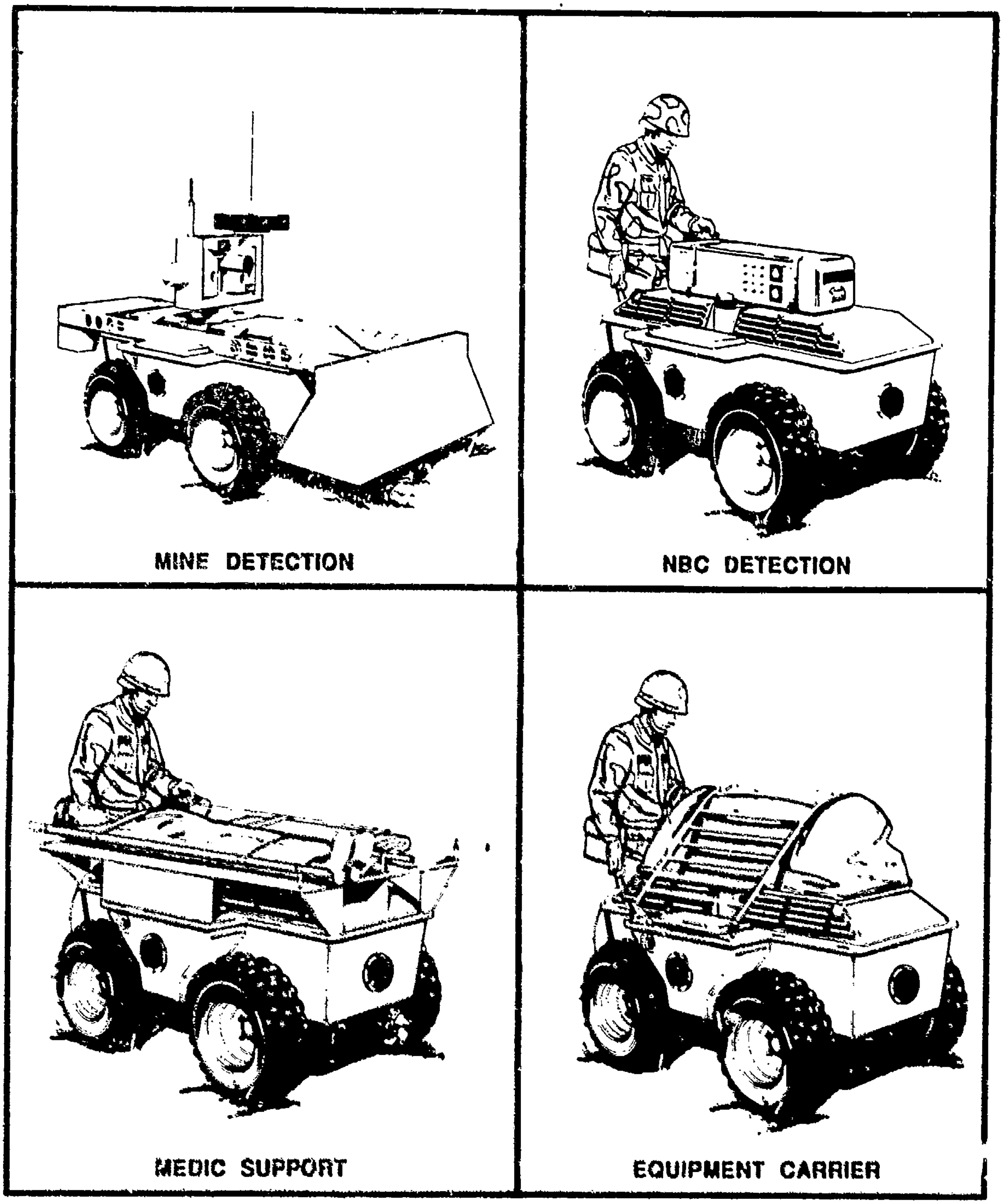

FIGURE 9 (CONT.): TMAP ALTERNATE CONFIGURATIONS

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WHEN WILL ROBOTS BE USED IN COMBAT?

20 April 1988

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ABSTRACT

This brief paper explores the question "When will robots be used in combat?" To this end, the advantages of battlefield robots are compared with manned options in terms of cost-benefit ratio and probability of success. If a conservative policy for the employment of robots is assumed to predominate for the next several years then robots must have lower costs and higher probabilities of success than manned systems to be employed in significant battlefield roles. Robots will easily attain lower mission costs before they will assure higher probabilities of success than manned systems. Inherent complexity in design and implementation, the lack of implementation and operation experience and a poor understanding of the issues of robot to operator mapping will keep robots to only the simplest and most dangerous tasks for some time to come.

INTRODUCTION

Recently, considerable interest in applying automation to various areas of the operational military has developed as a result of the increasing cost of battle and the increasing sophistication and numbers of the potential threat. Much attention has been focused upon automation for combat in the hope that it will make the battlefield more survivable and will multiply the capabilities of human forces sufficiently to intimidate an enemy with vastly superior conventional resources. The increased interest is, as a whole, good if it can be sustained through a necessarily long development period. However, there is significant danger that unrealistic expectations of time scale and feasible capabilities could be built in the user community by overzealous automation advocates. Eventual success at realizing practical battlefield automation will only come if researchers, developers and users alike maintain a realistic perspective of the roles which automation can play in the modern battlefield.

This brief paper is dedicated to sharpening the collective understanding of where automation can best be applied by exploring the question "When will robots be used in combat?" Two definitions are needed before this discussion can begin. The scope of these definitions is limited strictly to the purposes of this paper and should not be interpreted as being broadly applicable to other circumstances.

Definition 1: Battlefield automation is any form of computer assistance to human operations in the battlefield.

Definition 2: Battlefield robots are a subset of battlefield automation and are devices which are coupled directly to the battlefield environment through both sensing and actuation.

The first definition includes all computation applied to combat and direct combat support. The second definition specifies only those devices which interact directly with the friendly and hostile elements of the battlefield. Directly, in this definition, means not through a human operator. For instance, automated target cueing is battlefield automation which is not in the class of battlefield robots because the actual prosecution of targets is handled by a human. On the other hand, this definition of battlefield robots includes both teleoperated, as well as autonomous, systems since in a teleoperated device the human interacts with the battlefield environment through the remotely controlled surrogate.

These definitions distinguish between two forms of automation, robots and automated assistance to manned resources. Currently, considerable interest exists in the applications of robotics to combat to reduce human exposure to hazardous conditions. This paper specifically examines the issue of applying robotics to combat tasks. The application of other forms of automation to the battlefield will not be considered here.

THEORY

Robots will be used in combat when it appears that they are the best choices. Determining when they are the best choices requires measures through which robot performance can be compared with the performance of the alternatives.

Comparison Measures

A common measure used to determine when robots will augment or displace human labor in the factory is return on investment. Typically, robots perform simple repetitious tasks better and often faster than humans. In the factory, robots improve product quality and quantity by improving the consistency and speed with which many simple operations can be performed again and again. Improved product quality and production rate provide obvious quantifiable returns on robotics investments. Unfortunately, the battlefield is not like the factory where much of the environmental complexity can be well structured. The battlefield is a complex place where predictable repetition is quite dangerous. This implies that robots have no inherent quality or speed advantage over conventional manned systems since manned systems will perform unstructured tasks better than robot systems for the near future. Therefore, product quality and production rate, two measures traditionally used to determine robot utility, are not meaningful in the combat situation.

One meaningful measure of combat system effectiveness is cost- benefit ratio. It seems reasonable to say that robots can be employed effectively only when the cost-benefit ratio is better than that of manned systems for the same mission. This would be the case in a very hazardous mission where there is an opportunity to save human lives since the cost of a human life is very high. Unfortunately, cost-benefit ratio by itself is insufficient to decide between the use of manned and robot systems in combat. The battlefield is a highly uncertain place and even if the cost-benefit ratio for a robot option is very good it is not likely to be chosen unless it has a reasonable chance to accomplish the designated mission successfully. Thus, both cost-benefit ratio and probability of success must be used to determine when a robot will be employed in combat. Today, the probability of success of any robot system in any real battlefield situation is low for all but the simplest of tasks.

Comparison of Robot and Human Alternatives

Comparison of robot and human forces for battlefield operations begins with the statement of several assumptions and the identification of the components of the cost-benefit ratio and the probability of success. These components are compared term by term to determine where robots excel over humans and where they fall short. The situations where robots excel are assumed to be those circumstances when robots are likely to be employed.

The first assumption states the philosophy a field commander would use in trying to decide between using robot and manned forces. In this philosophy, a commander of forces with both manned and automated assets will choose the options with the best cost-benefit ratio and probability of success. Stated more formally, this assumption is saying:

Assumption 1: A commander will choose the robot option if and only if

$$N_m / N_r > 1 \tag{1}$$

and

$$P_m / P_r > 1 \tag{2}$$

where

N_r = the cost-benefit ratio of using robot assets for a particular mission,
N_m = the cost-benefit ratio of using equivalent manned assets for the same mission,
P_r = the probability that the mission will be accomplished using robot resources and
P_m = the probability that the mission will be accomplished using manned resources

and where the cost-benefit ratio for a system x to perform a certain mission, A, is defined by

$$N_x(A) = C_x(A) / B_x(A) \tag{3}$$

where

$C_x(A)$ = the cost of employing resource x to accomplish mission A and
$B_x(A)$ = the benefits of accomplishing the mission A with the resource x.

Equation (3) makes the ratio

$$N_m / N_r = (C_m(A) / C_r(A)) * (B_r(A) / B_m(A)). \tag{4}$$

The formal statement of Assumption 1 is somewhat stronger than the informal statement given above by requiring that automated options excel in both cost-benefit ratio and probability of success. This could be considered the policy of a conservative commander who is skeptical of automation. Considering historical precedent, this policy is likely to dominate the military for many years.

Assumption 1 reduces the problem of determining where robots can best be used in combat to looking at the ratios of cost-benefit ratios and probabilities of success for conventional manned assets and proposed automated assets for various missions of interest. Let us examine the issues associated with computing these ratios.

Cost-Benefit Ratio

Equation 4 can be simplified with another assumption which does not severely violate rationality.

Assumption 2: The benefits of any mission are completely independent of whether manned or automated forces are used to accomplish the task or

$$B_r(A) / B_m(A) = 1. \tag{5}$$

Substituting Equation (5) into Equation (4) produces

$$N_m / N_r = C_m(A) / C_r(A) \tag{6}$$

which reduces Equation (1) to

$$C_m / C_r > 1. \tag{7}$$

The costs used above are not simply the costs of purchasing the systems employed nor are they just the costs of operating the systems being compared. As implied these costs depend upon he specific mission in which they are employed, upon whether the system is lost during the mission and upon how many related casualties are sustained during the operation to execute mission A. An additional assumption is useful to simplify this computation somewhat.

Assumption 3: The commander delegated with a mission will assume the worst case outcome (i.e., complete mission failure, complete system loss and worst case associated casualties) when computing the cost ratios.

This makes the cost for employing system x in mission A a tractable, albeit difficult, computation. One possible formulation of the components of cost is

$$C_x(A) = C_x + C_o(x) + C_c(A) + C(A) \tag{8}$$

where

C_x = acquisition cost of system x,

$C_o(x)$ = operations cost of system x,

$C_c(A)$ = cost of the casualties associated with the failure of mission A and

$C(A)$ = cost of the failure of mission A.

There may be other better candidates for computing system-mission cost. This suggestion merely highlights the need to include costs in addition to the system acquisition cost and to include both mission dependent and system dependent components. In addition, the system cost (both operations and acquisition) is strongly related to the complexity of the technology which may, in turn, be related to the probability of success. However, for the sake of simplicity, these couplings are assumed to be negligible.

Substituting the results of Equation (8) into Equation (1) produces

$$C_m / C_r = \frac{C_m + C_o(m) + C_c(A) + C(A)}{C_r + C_o(r) + C_c(A) + C(A)} . \tag{9}$$

Even considering the present state of the art in robotics, the acquisition cost for robots is likely to be less than the cost of a manned system for a similar mission. This is especially true for teleoperated systems since much of the most costly parts of the system are theoretically placed out of harm's way. The operations costs are likely to be more when using humans than when using robots since manned assets generally require more support than robot assets. The cost of casualties in the event of mission failure will only be somewhat less for robots than for manned options because the largest component of near term forces will likely be humans for either options. Finally, the cost of mission failure will be equal for both manned and robot forces. From these crude estimates, it is possible to venture that the cost ratio for manned and robot options could be close to unity. This is even more likely to be true for robot assets which are actually deployed since the purchase and operations costs must be less than or equal to the equivalent costs for manned assets for the concept to get past the early stages of development.

Probability of Success

Comparison of automated and manned options in terms of cost-benefit seems to be relatively easily computed. Computation of the relative probabilities of success is not as straightforward. The way in which missions are stated must be limited to establish a concrete definition of probability of success.

Assumption 4: The mission is stated so that it is either a complete success or a complete failure (i.e., no partial success).

This assumption enables the association of the probability of mission success using system x with the probability of failure through the relation

$$P_x = 1 - F_x . \tag{10}$$

Equation (10) together with Assumption 4 permit the probability of success to be computed directly from knowledge of the probability of failure. This convenience enables the statement of the probability of success in terms of more readily available factors (e.g., system failure rate) and permits the transition from speaking of success to speaking of failure. One can argue that the ratio of the probabilities of failure is just as useful as the ratio of the probabilities of success for deciding what assets are best employed for a certain mission although they are not equivalent mathematically. To state further arguments in terms of failure requires an additional assumption to clarify the situation.

Assumption 5: Only failures which cause complete mission failure will be considered in computing the probability of success for system x.

This assumption neglects an entire class of noncritical errors and system failures which do not cause the mission to collapse. While these problems are significant, they are, for the most part, a nuisance and can be expected from both manned and automated systems for some time to come. Critical errors, or the probability of critical errors occurring, will largely determine how useful systems are to combat situations. In addition, many errors which are negligible in factory environments become crucial in combat.

The probability that system x will succeed at mission A can be stated as the following combination

$$P_x(A) = P_{x'}(A) * P_e(x) \tag{11}$$

where

$P_{x'}(A)$ = probability of mission success with no critical system errors and
$P_e(x)$ = probability of no critical system errors occurring in system x.

The first term in Equation (11) represents the probability of mission success given perfect system operation. This term can be decomposed into the following components:

$$P_{x'}(A) = P(x:A) * P(x:0) \tag{12}$$

where

P(x:A) = the probability of mission success if system x is operated perfectly and
P(x:0) = the probability that system x will be operated perfectly.

The first term in Equation (12) measures the match of the system capabilities to the task. Simulations are especially valuable for obtaining estimates of this term for various systems and mission scenarios. The second term represents the effectiveness of the operator (if there is one) and

$$P(x:O) = f(\text{operator state, training and interface}). \qquad (13)$$

This term can be difficult to evaluate but the human factors community has developed techniques to make theoretical estimates and to determine experimental approximations.

The second term in Equation (11) represents system reliability in a certain mission. This term can be further decomposed into two components

$$P_e(x) = P_{es}(x) * P_{eh}(x) \qquad (14)$$

where

$P_{es}(x)$ = probability that no software failures will occur in system x during the mission and
$P_{eh}(x)$ = probability that no hardware failures will occur in system x during the mission.

Equation (14) divides failures into the two major components of a robot, hardware and software. Failures can also be orthogonally partitioned into soft errors and hard errors. Soft errors are transient errors (i.e., errors which occur once and then disappear). These can occur in hardware (e.g., memory errors from alpha particle hits) as well as software. Hard errors are permanent failures and may also occur in software (through a system crash) as well as hardware. The effects of hard and soft errors are especially difficult to evaluate for automated systems. More reliable failure statistics are available for hardware subsystems than for software. However, further experience with automated systems in various operations will provide some basis for better quantification of these errors in the future if the proper experimentation is performed.

Thus, combining the above results, Equation (2) becomes

$$Pr \,/\, Pm = \frac{P(r:A) * P(r:O) * P_{es}(r) * P_{eh}(r)}{P(m:A) * P(m:O) * P_{es}(m) * P_{eh}(m)}. \qquad (15)$$

For the sake of argument, consider an additional important assumption.

Assumption 6: For every manned capability there is a corresponding and equal automated capability, i.e.,

$$P(r:A) = P(m:A). \tag{16}$$

This assumption represents the futurist's perspective by predicting a time when, in terms of mission success, it will make no difference whether a robot or manned system is employed. As such, it casts robot options in the most favorable possible light for the remainder of this discussion. Assumption 6 reduces Equation (15) to

$$Pr / Pm = \frac{P(r:O) * P_{es}(r) * P_{eh}(r)}{P(m:O) * P_{es}(m) * P_{eh}(m)}. \tag{17}$$

The terms representing manned systems in Equation (17) are reasonably well understood when compared to the corresponding terms for automated systems. Further, the probabilities of no software and hardware failures for robot systems will be considerably lower than the corresponding terms for manned systems because of the higher information processing machine complexity and associated failure modes. The corresponding probabilities for manned systems will be higher because of the significant body of experience in constructing manned combat systems. This very situation could well determine the fate of robots on the battlefield for the next several years. In the early development period of combat robots, the probability of no operator failures will be much less for robots than for equivalent manned systems because of the large amount of experience in training humans to operate manned combat equipment. Much remains to be learned about training people to operate combat robots and this void will directly affect their probability of success. From this crude comparison, it is easy to see that manned systems will have greater probabilities of success for years to come simply because of the great vacuum of experience in applying robots to combat.

When comparing totally autonomous systems with teleoperated systems, the probability of no operator failures is nearly unity for an autonomous system. However, the probabilities of no software and hardware failures in autonomous systems may be somewhat lower than in teleoperated systems because of the inherently higher complexity. However, as robot systems are used more and more the probabilities of no software and hardware failures get larger and larger as many of the latent failure modes are discovered and eliminated or improved. Thus, it is likely that the probability of success for autonomous systems will eventually be significantly better than for teleoperated systems. Note that all of the above comments are only valid if the cost of automated assets is less than the cost of equivalent manned assets.

Influence of Policy Changes

The policy used to decide between manned and robot forces ultimately determines when robots will be used in combat. This analysis initially assumed a conservative policy because it seems most consistent with traditional military decisions and because it is the easiest to analyze. Other employment policies are possible. If the requirement that robots must have a probability of success greater than or equal to that of equivalent manned systems is relaxed then robots would, of course, see much greater use. However, this policy is contradictory with the real goal of military commanders, i.e., to win the war. Winning against an able adversary requires a very good resource allocation strategy. The optimal allocation strategy would include applying the assets best suited for the job (i.e., those with the least cost-benefit ratio and the greatest probability of success). Choosing a less optimal strategy only increases the chances for defeat. Thus, the policy which forms the basis of this analysis is part of the optimal strategy for winning and is the most likely to be employed not because of tradition or ease of analysis but because it is required to win at battle. Any different policy would result in failure and greater loss of life.

CONCLUSIONS

This analysis has introduced a technique for determining when robots will be used in combat and provided some insight into the likelihood that robots will be employed in combat in the near future. If one assumes that the conservative philosophy will predominate for the next several years then robots must have lower costs and higher probabilities of success than manned systems to be employed. Robots will easily attain lower mission costs before they will assure higher probabilities of success than manned systems. Inherent complexity in design and implementation, the lack of implementation and operation experience and a poor understanding of the issues of robot to operator mapping will keep robots to only the simplest and most dangerous tasks for some time to come.

Although this analysis is preliminary, the following conclusions can be drawn:

Conclusion 1: Defensibly determining when robots are best is not possible until their costs and probabilities of success can be accurately estimated.

Conclusion 2: The method outlined above provides a concrete technique by which to compare manned and various forms of robot assets for well defined missions. Hard numbers either are or should soon be available for each of the criteria discussed. These can be determined through simulation, experimentation and combinations of the two.

Conclusion 3: The major near-term contribution to combat from robotics will come in the form of automated assistance to manned assets. The present and near future costs are too high and the probability of success too low for automation in the form of autonomous and teleoperated systems to be realistically employed directly in combat for some time.

TMAP: An Offset Platform

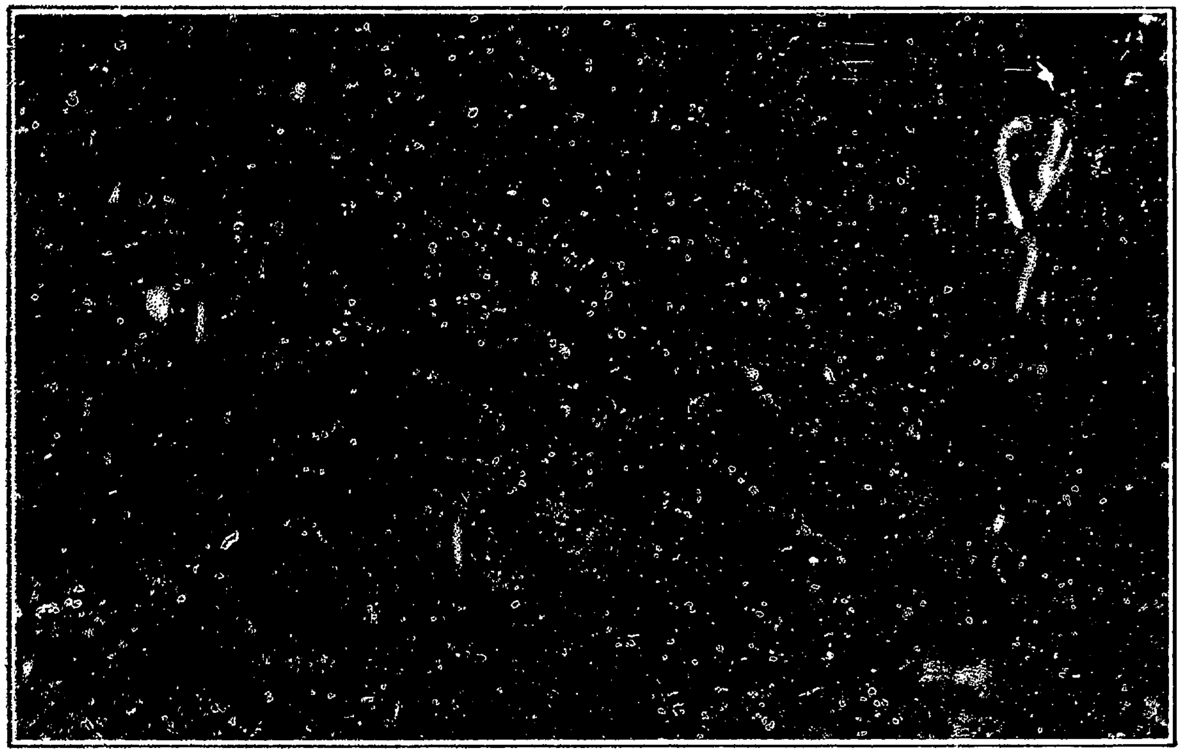
Jerome Kirsch
Grumman Corporation

(PAPER NOT SUBMITTED FOR PUBLICATION)

(VIEWGRAPHS ONLY)

TMAP
An Offset Platform

Teleoperated Mobile Antiarmor Platform



B671V.001

GRUMMAN®

Electronics Systems

B671V.002

TMAP

An "Offset" Platform

J. Kirsch
Guided Weapons Systems Products
Robotic Vehicles

June 1988

Preface

Contractors have been directed to remove weapon payloads from TMAP during the current Proof of Principle phase. Weapons discussions apply in a generic context only.

B671V.004

Teleoperated Mobile Antiarmor Platform

Proponent	U.S. Army Infantry School, Fort Benning, GA
Developer	Sandia National Laboratory, Albuquerque, NM for U.S. Army Missile Command, Redstone Arsenal, AL
Contractors	Grumman Electronics Systems & Martin Marietta. [illegible] of principle awards 7/15/87
Background	[illegible] U.S. Army/Grumman conducted concept/simulation with Grumman Robotic Ranger

B671V.036

Illustrative Offset Requirement

"You have to keep the cross hairs on the tank for 15 to 20 seconds or else you won't hit it. A T72 can swing its gun around & kill you in four seconds."

"When fired, the dragon sends up a highly visible, distinctive plume of white smoke, . . . " *

* February 28, 1988 Huntsville Times article on Fort Irwin training exercises

B671V.007

Additional Benefits

- Monitor/secure high ground, wooded areas/choke points with extended endurance/reduced manpower
- Deal with intense fire density, directed energy weapons
- Probe, mark & traverse suspected FASCAM & off route mine fields. Probe & mark unexploded ordnance
- Detect, measure & mark battlefield contamination; CBR
- Conduct other high risk operations with sacrificial willingness, such as:
  - Close-in battle damage assessment
  - Selective smoke dispensing
  - Bunker busting
  - Re-supply
  - Laying of field wire (F-O)
  - Demolition of facilities
  - Rear guard
  - Drawing & locating enemy fire

How Mobile Are These Small Vehicles?

- Small vehicles have negotiated terrain usually reserved for larger, more powerful manned vehicles. Unique longstroking suspensions are the key to even more impressive performance
- Small vehicles have limited crushing, but good flotation. Demonstrated at Ft Benning

How is TMAP Transported?

- Delivered conventionally to staging area, then self transportable. Perhaps more trips required
- Fits in a HMMWV.·.compatible with most other transportation assets
- Easy to manhandle. Towable in "trains"

How Does It Fit Infantry Organizational Structure?

- Proof of principle completion will characterize TMAP to determine what organizational structure changes are advisable to achieve new benefits

The first airplane suggested for military use didn't fit the then current structure. Robots like airplanes were destined for the battlefield irrespective of existing organizational structure

How Do We Position TMAP?

- For defensive missions, TMAP's can be:

  (1) Tether or remote controlled and/or "hand" emplaced off road, similar to an off route mine

  (2) Similarly placed at vantage points overlooking roads, intersections and corridors of approach

- For offensive operations, TMAP can aggressively establish new positions & "pull" fire for purposes of locating enemy positions

B671V.011

Can't F-O Cable Be Cut with a "Scissors?"

- Offensive operations done on timely basis. No time to look for a camouflaged $<<0.1$ inch diameter cable on the ground, let alone survive to find & cut it
- Defensive operations have the cable emplaced off road
- Long term, communications field wire precedents
- Currently no other low cost communications alternative will operate securely & reliably at real time video bandwidths beyond line-of-sight. Practical alternatives are perhaps a decade or more away

B671V.012

Can't TMAP Be Replaced with a Tripod?

- No
- Beyond line-of-sight, <u>mobile</u> TMAPs can:
  - Gain valuable high risk vantage points
  - Aggressively probe to pull & locate enemy fire power
  - Sweep areas containing FASCAM fields & off route mines
  - Lay communications cable (F-O) under fire. Inherent in TMAP - just plug in
  - Move from concealed "acquisition" locations to open fire
  - Systematically search CBR contaminated fields
  - Disperse robotic smoke at high risk locations (bridge entrances et al) & or corridors of approach
  - Sacrificially attack bunkers

Next Steps

Reduce Workload & Increase Ground Control per Soldier

- Automatic techniques including video MTI & multi-spectral non LOS cuing
- Sensor blending utilizing symbolic processing algorithms plus optical correlators
- Note that the percentage of false alerts tolerated can be relatively high

B671V.014

Next Steps (Cont'd)

Dynamic Mine Fields & barriers

- Few soldiers channel rapid advances into killing zones
- Soldier coordinates reconfigurable "daughter" mines via TMAP "mother"
- Dendritic deployment configurations
  - Failure tolerant
  - Cooperating dispersed elements provide new benefits i.e., allows more accurate positioning etc
- All important man in the system

B671V.015

Other Significant TMAP Benefits

B671V.016

TMAP Weapons Issue

- AT-4 missile will not penetrate active armor or frontal glacis of modern Soviet tanks

Answers

- AT-4 was a baseline for proof of principle purposes as it is currently in army inventory
- AT-4 is an anti-armor weapon. There are ample targets - 80,000 Soviet armored vehicles *
- Offset platforms will have more opportunities for side & aft attacks than manned forces
- For main battle tanks, offset platforms can deploy AAWS-M. AAWS-M is on the same development schedule as TMAP

* Defense news 11/16/87

B671V.017

TMAP - AT-4 Synergistic Results

"$800" AT-4 becomes a precision fire control weapon; potential clearly demonstrated during robotic ranger concept evaluation program

- Lead angle & ballistic compensation
- Stable TMAP weapons platform vs soft shoulder
- No "pucker factor". Safe soldier deploys robot aggressively
- High power zoom optics (day or night) vs unaided post & peep sight
- n more missiles with adjusted aiming, if first launch misses
- "Stays around" for real-time battle damage assessment
- Weapon system range = TMAP range + AT-4 range - - - a range extender

Reduced Time for Fielding Man-Rated Weapons

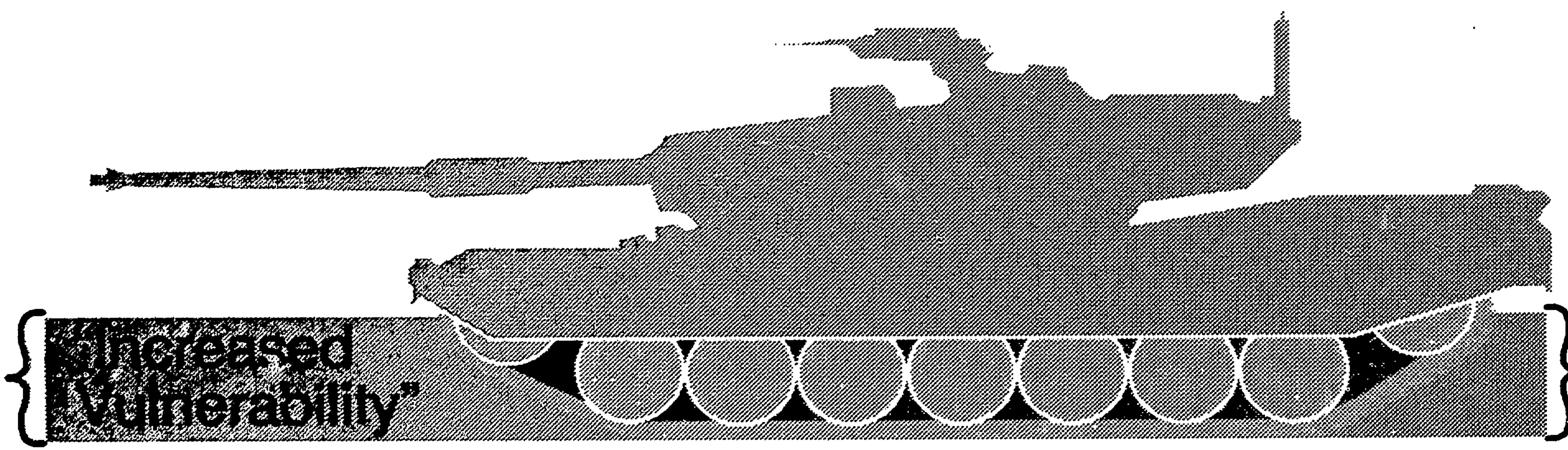
- Microwave weapon platforms (side lobes may be too lethal for manned platforms)
- "Fire-ant"* weapons

* Sandia National Laboratory Concept

B671V.019

Greater Opportunities for Mobility Kills

- Increased targeting precision
- Closer range
- Multi (low cost per round) shots



Summary

TMAP offset platform functions as an "extension" of the soldier, allowing him to operate his optionally expendable robot in

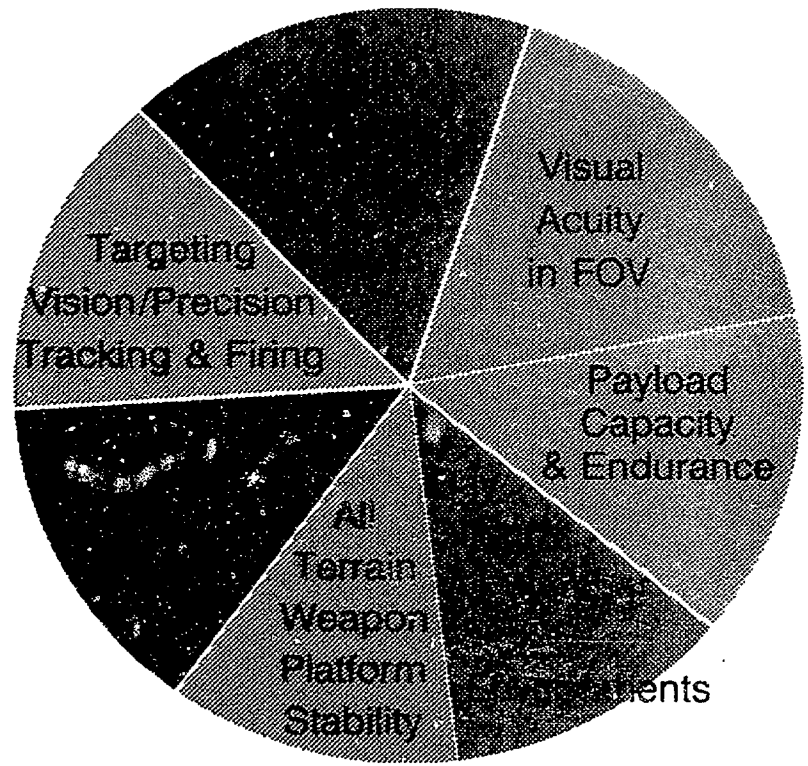
- Intense lines of fire
- Battlefield contaminants (CBR)
- Sacrificial missions (demolition et.al)
- "Robotic smoke" missions - - - "Barrier 21" payloads
- Aggressive reconnaissance missions
- Anti-armor missions
- Sentry missions
- Safe lane operations (thru FASCAM fields)
- Firebase surveillance & protection operations
- Sacrificial bunker busting missions
- Close-in battle damage assessment missions
- Critical re-supply operations
- Communications cable laying operations
- Operations against laser & microwave weapons or inversely carrying microwave weapons et. al.

B671V.02

Robotic Offset Platform

Limitations

Attributes



Combining the best attributes of man & machine will require new tactics & provide unprecedented battlefield advantages

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Session III Program A

Artificial Intelligence and Expert Systems I and Image Processing

Chair: Elaine Hinman, NASA/MSFC

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AN EXPERT SYSTEM FOR OBJECT RECOVERY

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ABSTRACT

Expert systems are being built to serve as intelligent advisors and decision aids in a wide variety of application areas. An expert system is being developed to capture the essence of locating and recovering objects from the sea floor with the aid of a remotely operated underwater vehicle. The expert system is capable of evaluating the at sea situation and dynamically modifying the search and recovery strategy to optimize operations.

INTRODUCTION

Expert systems offer a great deal of utility in assisting humans in a variety of domains. The explicit codification of knowledge is an illumination process which leads to many new insights within a particular domain. A primary goal of creating an expert system is to make existing knowledge inexpensive and available. In today's society, hard problems that require the best human expertise are greatly prolif-rating as technology becomes more complex. As expert systems are capable of dealing with large solution spaces known to be hard for humans, expert systems actually extend the type and degree of problems that can be solved. An expert system places extensive problem solving knowledge in the hands of less trained operators.

In recent years there has been a great expansion in the application of underwater Remotely Operated Vehicles (ROV's) within the Navy support community. What typically characterizes ROV operations for Navy use is a large number of standard tasks which have a great deal of variability associated with them. The knowledge associated with similar or repeated (engineering) logs. To date, the efficiency and effectiveness of the ROV operations have been highly operator dependent. Clearly an opportunity exists for a knowledge base system to assist the operator in recalling, processing, and interpreting information.

Underwater navigation and positioning is a critical task. The information needed for underwater navigation and positioning comes from a wide variety of ROV onboard sensors, shipboard sensors, and often bottom mounted sensors. What the operator needs the most is the interpretation of sensor data to form an electronic chart that maps out a route.

Expert system technology driven by real-time situation data, combined with man-machine interface techniques can provide a tool that capitalizes on this opportunity by amplifying human data fusion capabilities. A knowledge based paradigm supporting data fusion with man-in-the-loop is described for a specific application of underwater object recovery. The operational concept includes a decision aid to associate and combine multiple source data arriving in real-time. Due to the complexity and the dynamic nature of the environment, the monitoring of such a multi-media system entails the effective management of information and timely decisions in terms of what adaptation options are available or recommended. The thrust of the current work has been in developing a workstation that allows the operator to quickly and easily access the most relevant information.

The approach considered in this study is the application of Artificial Intelligence (AI) techniques, the expert system approach in particular, to the object recovery process. This paper discusses the expected application of these AI techniques in the operational system and describes the efforts and accomplishments of the system development. The work underway for TONGS will lead to a better understanding of applying AI technology to the marine environment.

Television Observed Nautical Grappling System Background

The Television Observed Nautical Grappling System (TONGS) in current use at the Naval Surface Warfare Center (NSWC), Fort Lauderdale Facility, has evolved over a number of years in response to operational needs[1]. TONGS was just utilized in shallow depths to assist Navy divers in planting and recovering objects on the sea floor. The objects usually mated to an underwater, armored coaxial cable laid from the beach. TONGS assisted the divers by providing a means to guide a lifting cable from a shipboard crane to the immediate area of the bottom-mounted object. As the water depths increased, the usefulness and efficiency of the diver teams decreased. The consequences of the diver imposed depth and bottom time limitations spawned the first TONGS sensor, a closed-circuit television for monitoring underwater operations. TONGS would sit on the sea floor, and surface operators could observe nearby diver operations via the remote TV camera.

Successful follow on operations provided impetus for further refinements and a family of TONGS type vehicles evolved. TONGS was progressively developed as the primary system to locate the sea ends of cables, recover the cable end to a surface platform, then orient the object of interest on the sea floor. As experiments progressed into deeper water TONGS capabilities were upgraded to remain functionally sufficient to provide support for a variety of test programs.

Locating and recovering an object or target is a time consuming and sometimes frustrating job. Even if you think you know where an object is being placed on the sea floor, the basic dynamics of the ocean currents acting on the ship and TONGS guarantees an uncertainty in actual location of an object on the sea bottom. TONGS has search and acquisition capability compatible with environmental conditions at operational depths. In early TONGS configuration, location of an object was accomplished with a narrow-beamed, directional hydrophone (listening hydrophone) used in conjunction with an acoustic beacon to provide a general bearing in the direction of

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[1] W.A. Venezia, G.A. Lamb, B. Dixon, "Television Observed Nautical Grappling System (TONGS)", MTS/IEEE ROV 84 Conference, pp 240-244, 1984.

the object . An active sonar with a conical beam in conjunction with a sonar reflector provided range to the object. Both the hydrophone and the active sonar were aimed along a common axis controlled by a pan and tilt mechanism. A compass provided a continuous indication of the direction of the pan axis. Unfortunately, the missing object isn't the only thing on the ocean floor and the operator must investigate every signal returned by the sonar.

Over the years the TONGS's sensors have been upgraded to include Obstacle Avoidance Sonar, local area positioning systems, and a variety of sensors for measuring the environment. The use of multiple sensors for target recovery provides both redundant and complimentary coverage of the target observation space. The sensors to be utilized by the expert system are a pressure transducer, compass, Obstacle Avoidance Sonar, black&white TV camera, Surface Tracking System, NAVTRAK, and underwater tracking system.

EXPERT SYSTEM OVERVIEW

The expert system is designed to perform tasks such as: data reduction and interpretation of sensor measurements, diagnostics, and advise the TONGS operator and ship navigator. This interactive and user friendly system uses a high speed large capacity inference engine architecture in a PC microcomputer hardware environment, and has an established knowledge base with sufficient levels of detail to produce guidelines in the form of suggestions along with supporting criteria.

A functional block diagram of the operational program is presented in Figure 1. The overall system is depicted in terms of the functional interfaces of the system and its major functional modules: sensors, the expert system, and user interface. These modules are independently developed, and evaluated. Then they are integrated into one coherent package. Note that the expert system accesses TONGS onboard sensors, shipboard sensors, and bottom mounted sensors through appropriate interfaces. The expert system is composed of: inference engine, knowledge base, and control functions. The knowledge base contains facts and databases. Target data from sensors and any update performed by the navigator and the operator is used to update the databases within the expert system module. As changes in the recovery situation are perceived, the program reassess the situation and provides advice to the operator as appropriate. These suggestions include the selection of optimum paths and information regarding any known targets in the vicinity of the operation.

Having received an operator command, the expert system interrogates the operator and the target data for information regarding the environment and possible targets. Based on the current system states, the expert system chooses the sensors/modes of operation to achieve the operator objective while maintaining efficient operation of the overall sensor suite. The input stage will allow software control of the process by which a new user can effectively turn on the system, access it, and receive coherent, correct responses from the system. The input procedures are human-engineered to reduce obvious errors, and ease user interaction with the system.

The integration of the expert system, user interface graphics, and database modules (Figure 2) is the most challenging original programming in the critical path of system development. This is due to the complexity of interfacing off-the-shelf packages such as GoldWorks, PC-Paint, HALO Graphics, and dBASE III Plus. Significant amount of software linkage was required between these packages to establish an efficient interface.

DATA STRUCTURE

The knowledge is scattered among a set of modules that have access to data in the database and may post their findings on any level of the databases. There are two databases accessible by the expert system: Navigator Log database, and Cables database. The Navigator Log database contains information describing the events occurring onboard the ship. From the time the ship leaves port until it returns to port, a description of all activities and observations concerning the mission is entered into the database. Compilation of all this data forms a knowledge base which can be used by the TONGS operator. The knowledge base allows the operator to make quick decisions based on all the available data. For example, suppose an operator needs to recover an object and he knows the general area where it can be found. The database can be queried for information regarding known objects in that area. Therefore, known objects won't be mistaken for the missing object and significant time is saved.

Each activity or observation during a mission is stored in the database as a separate record and thus each mission will typically have several records. A record contains information such as: the date of the mission, the time a record is entered, a description of the activity or observation, a description of the object to be recovered, the X and Y position of the object in a local area coordinate system, and the depth of the water at these coordinates.

One activity performed by the ship's crew is to lay cable and/or repair cable. As a cable is laid on the ocean floor, pertinent information about it is stored in the Cables database. The information considered is: the cable number, a physical description of the cable, the coordinate system used to calculate the X and Y cable coordinate, the cable-end coordinate, the depth of the water, and owner of the cable. The Cables database can be thought of as a map of all the cables laid on the ocean floor. This data is particularly useful to the operator when searching for a cable (either to pull it up or to make a repair to it).

The Navigator Log and Cables databases are integrated into the TONGS expert system to act as a knowledge base. Therefore, when the operator needs information from the database he has the option of querying it directly or accessing it through the expert system. Because the operator and navigator are constantly updating the databases, the expert system can base its decisions on up to the minute data. Eventually some of the data won't need to be entered manually by the operator; instead, the hardware will be interfaced so the readings from the sensors will automatically update the databases. An effective software interface is established with dBASE III Plus through the implementation of software command routines. Data files are designed to apply labels, construct tables , modify, add or remove records via dBASE III Plus subroutine calls.

EXPERT SYSTEM

Expert knowledge in the forms of factual information, procedural rules, meta-rules, and heuristics (all of which are elements of an individual's knowledge and experience in his field of expertise) can be captured and transferred to an intelligent computer program which uses inference procedures to emulate the problem-solving and decision-making performance of the human expert whose knowledge or experience is represented in the program. The principal issues in building a knowledge based expert system involve: acquiring domain specific knowledge from recognized experts, representing that knowledge appropriately in the system's knowledge base, and using that knowledge effectively for decisions and problem solving. The data stored in the two databases is evaluated by the expert system to infer recommendations for the TONGS operator to find a missing object based on similar past situations.

The TONGS expert system has several layers of embedded software as shown in Figure 3. In the center, are Common Lisp and C programs. The next layer contains dBASE III Plus, followed by graphics and the GoldWorks expert system shell. The outermost layer is the expert system. Because it is the outermost layer, the expert system can utilize not only the GoldWorks shell, but the dBASE III Plus, Graphics utilities, Lisp and C languages as well. The expert system utilizes this feature by supporting the GoldWorks rules with functions coded directly in Lisp.

The development cycle of an expert system can be decreased if an effective expert system tool is used such as GoldWorks. This system combines frames, rules, and object programming into a single integrated system.

GoldWorks runs on PCs and can be interfaced to dBASE III Plus, and C. This system uses frames to structure information in the knowledge base. Frames are templates for inserting information about objects into the knowledge base and are organized in a hierarchy called a Lattice. Frames are named and have attributes called "slots". An instance is built from a frame and inherits the slots of the frame. Values within slots can be controlled by rules and by attributes called "facets". GoldWorks is installed in a PC-AT microcomputer with a HummingBoard. The HummingBoard incorporates the Intel 80386 running at 16 MHz, high speed cache with 8 megabytes of RAM. This board was designed to transform a conventional PC into a Lisp machine, thus increasing the performance of PC-based systems.

The present expert system is developed to recover a known object which is a cable, and to recover a known object which is not a cable. The system makes use of the Goldworks' Sponsor system to deal with the rules involved for each of these cases. Sponsors are used to control the resources allocated to the firing of the rules in a system. Under the sponsor system, rules are grouped together and only the required sponsors will be activated so that their rules may have a chance to fire. This will increase system response time. Using the knowledge obtained from the operator, the system, via rules, will access the appropriate database to discover relevant information and transfer it to the frame instances for use by the expert system.

Using information obtained from the databases as well as input from the various sensors, the TONGS expert system continuously calculates the range and bearing from the current position of the ship to the target site. Before TONGS is deployed, the system will use the database information to discover other objects which may be also be located in the area and thus help to hasten the location of the desired object. Once TONGS is within close range (ten feet) of the desired object, full manual control will pass to the operator for the final recovery operation.

Once an expert system is built, a large part of its usability depends on the end-user interface. Since most expert systems are really intelligent assistants, the end-user interface is often designed to allow interactive dialogue. This dialogue and/or initial input most often appear to the user as structured data input arrangements incorporating menu choices that allow the user to answer requests by the system for information. Also, text and graphics are often used to show line of reasoning when the system responds to user. Interactive graphics and simulation are used to increase the end-user's understanding and control of the system. The controls and displays provide an interactive interface for ease of command, data request, and data entry by the operator.

The expert system is designed to be useful to the TONGS operator and navigator. Information is condensed, clearly presented, easily assimilated and unambiguous so that there will be no confusion in the user's understanding. In this system, provisions are made to supply detailed or backup information when and if the operator wants it. The system user interface relies heavily on the use of three different graphics systems. The Goldworks' Screen Toolkit controls application screens and is used for the various popup menus in the system. PC-Paint is used for the creation of introductory screens, help screens, backgrounds and other static screens. The Halo graphics is intended for use with dynamic images. Examples of this include gauges, sonar displays, and other sensory input to the system. All of this information working together will give the TONGS operator quick access to the data he needs to make informed decisions instead of haphazard guesses.

SUMMARY

To effectively utilize the sensor suite and to reduce the number of operator tasks, a high level of automation is required. The TONGS expert system acts as a smart interface between the operator and the multi-sensor system for recovery of objects from the sea floor. This system provides advice to the operator in selection of optimum paths and to provide information regarding any known objects in the vicinity of the operation. The recovery process, and to present the data in an effective, and readable format. Results of the work to date show promise in demonstrating the use of an expert system in a practical at-sea operation.

ACKNOWLEDGEMENTS

The authors would like to thank Ms. Judith L. Hogan for her valuable contribution in developing the data structure for the knowledge base.

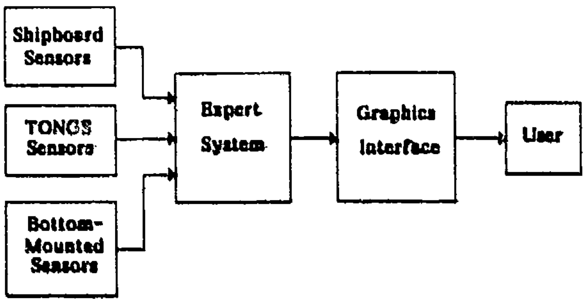

Figure 1. Overview of the system.

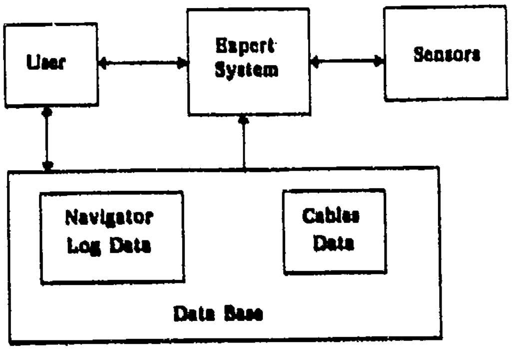

Figure 2. Expert system interfaces.

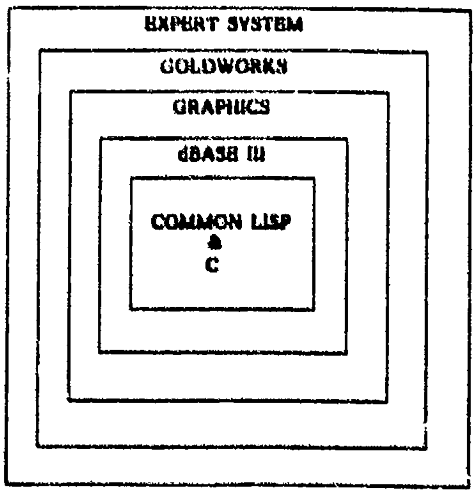

Figure 3. Components of the expert system.

High Level Intelligent Control of Telerobotic Systems

29 April 1988

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ABSTRACT

The authors believe that advanced telerobotic systems will involve both autonomous robot movement and user controlled robot movement. Although artificial intelligence can facilitate significant autonomy, a system that can resort to teleoperation will always have an advantage.

This paper proposes the development of a high level robot command language applicable to the autonomous mode of an advanced telerobotics system. The high level language will allow humans to give the robot instructions in a very natural manner. The system will then analyze these instructions to infer meaning so that the system can translate the task into lower level executable primitives. If the system is unable to perform the task autonomously, it will be capable of switching to the teleoperational mode.

1.0 INTRODUCTION

This paper presents an overview of a user directed object movement system (UDOMS) under development at the University of Alabama at Huntsville (UAH) that will, from high level user commands, plan the movement and generate the commands to move a robot in a known environment. The system is being developed on a Silicon Graphics IRIS 3020 interfaced with a PUMA 562 robot.

This system will combine the results of many researchers into a system that will go from user commands to robot movement. The user interface is by way of a graphical 3-D representation on the IRIS of the work environment. The user will select an object on the work environment by selecting the representation of the object on the graphic display and indicate where the object is to be moved by selecting another point on the display. The system will analyze the user command and if possible decompose it into a set of robot movement tasks. The system will then plan each task. Each plan will be a near-minimum time path for the robot that avoids any parts of the environment that may be in the robot's work space. The plan will also satisfy the constraints on the range, velocity, and acceleration of the joints of the robot and satisfy any constraints on the orientation and acceleration of the object being moved. The user may select to view a simulation of the proposed set of movement or have the system generate the commands for the PUMA. The PUMA will implement the commands enabling the verification of the robot movement plan.

ElMaraghy (1987) is implementing a similar system that seems to be concentrating on high level task planning. Grover (1986) has implemented a hardware system similar to UDOMS; it is a semi-autonomous system in which the user gives the high level commands to a robot. Neither work appears to include path planning in which objects are avoided and constraints on robot motion are considered. Fernandez (1986) has developed a system (ROBOSIM) that allow the user to plan complex movement of the robot in an off-line mode; but the programmer must do the path planning and must check for collisions.

The four major objectives in the development of UDOMS are: 1) to develop a high level language that will allow a user to manipulate the environment by way of the robot without having to know the details of the environment, the constraints on the motion of the robot, or the constraints on how the objects can be moved in the environment, 2) to define and develop structures for data bases that will contain the information about the robot, about the robot work environment, and how to move objects in the environment, 3) to develop an expert system to use the data in the data bases to transform the user commands into allowable robot commands, and 4) to create a system in which results of various researchers in the area of robot path planning can be combined into a working system to evaluate the performance of the various algorithms.

2.0 APPLICATIONS

Systems like UDOMS are ideal for use in telerobotic systems, deep space docking activities, and for generating programs for robots used in handling and securing hazardous materials and in the manufacturing environment. Telerobotic tasks may be divided into two categories: fine movement and gross movement. Fine movement is the movement involved in picking up or placing an object. Gross movement is the robot movement between fine movements. In telerobotic systems UDOMS is useful because 1) the environment in which the robot is working is known, 2) the user usually does not know all of the constraints imposed on the robot, 3) the user usually is not aware of all the parts of the environment in the robot's work space, 4) the types of feedback and time delays in the communication path make it difficult and time consuming for the user to control the robot, especially for the gross moves, and 5)the system can plan and make the gross moves of the robot, returning control to the user when the robot is in position that requires user intervention (fine movements). The type of feedback, type of controls, feedback time delays, and even the user personality affect the time required to accomplish telerobotic tasks, Crooks (1975), Farrel (1966), Yorchak (1985), and Collins (1985). UDOMS would be capable of implementing the gross robot moves without the need for any feedback to the user.

This type of system will also be applicable to manufacturing and testing environments in which the environment is known but changes frequently. Because of the user interface and on-line path planning the system can easily and quickly generate new path planning in response to changes in the work environment. It would not require a skilled operator to generate new robot programs.

3.0 SYSTEM DESCRIPTION

The system will consist of a set of processes as shown in the data flow diagrams, DeMarco (1978), shown in Figure 1 and Figure 2. Figure 1 shows the data flow diagram for the generations of the data bases for UDOMS. The structure of the robot will be defined in the form developed by Denavit (1955). Through a menu driven interface the user will supply the link and joint information for the robot being modeled. The user will also supply the limits on the position, velocity, and acceleration for the joints. Also through a menu interface the user will create templates of objects. The user will use the templates to create the environment by creating and combining objects. Everything in the environment is an object. An object can be a combination of other objects. Each object has a name, a geometric description, a position in 6-space (x, y, z, roll, pitch, yaw), a list of couplings to other objects, and a list constraints on how the object can be moved.

Figure 2 shows the data flow diagram for the command generator, movement expert system, geometric path planner, dynamic path planner, and robot command generator. The user views a projection of the 3-D environment on the screen of the IRIS. The user will be able to change the magnification and move through the environment by use of the mouse. The user will select objects by use of the cursor. When an object is selected the user will have the ability to examine any data about the object. Once an object has been selected the user indicates where to move the object by selecting the destination in the environment. The expert system contains the rules on how and where the various objects may be moved and the procedures for moving the objects. The expert system will determine if the movement is possible. If the movement is possible the expert system will decompose the move into a set of tasks for the robot. These tasks will be sent to the path planning processes.

Path planning will be an iterative process, between geometric planning and dynamic planning, of finding where the robot may move and then finding a near-optimum path that satisfies all the constraints on the system.

The geometric path planner process will find in 3-dimension space paths for the robot that will avoid any portions of the environment. The paths pass through knot points supplied by the expert system process. Lozano-Perez (1987a) gives a good overview to the work being done in geometric path planning. Most of the research on path planning, Lorazno-Perez (1987a), Kuan (1985), is either in the area of creating potential fields around objects and navigating along paths of lowest potential or partitioning the robot work space into areas of free space and finding paths through the free space. Gilbert (1985) approaches path planning as an optimal-control problem in which the objective function is either a minimum energy or minimum time of travel function. An algorithm along the line of Lozano-Perez (1987b), which presents a method of finding the free space in a robot's work space and a method of planning a path through the free space, will be implemented as the geometric path planner.

The dynamic path planning process will create a robot path that passes through the knots created in the geometric path planner and that satisfies the motion constrains on the robot and the object being moved. Two promising approaches to this problem are: fitting cubic splines to the knots, Lin (1985) and representing the problem as a near-minimum time objective function and using non-linear programming, Tan (1988). Both approaches consider constraints on the motion of the robot. The non-linear programming approach will be implemented in UDOMS. Once a path has been computed for the robot the geometric path planner process will verify that the path does not collide with the environment.

Once the path has been generated that satisfy both the geometric and robot dynamics constraints the robot motion can be simulated on the IRIS or robot commands can be generated and sent to the PUMA.

4.0 CONCLUSIONS

The authors believe that, even though the research is not complete, sufficient work has already been accomplished by researchers in the area of path planning that a usable high level system can be developed to plan and control the movements of a robot without the user having to know about the robot or the work environment. This paper discussed the design of such a system under development at UAH.

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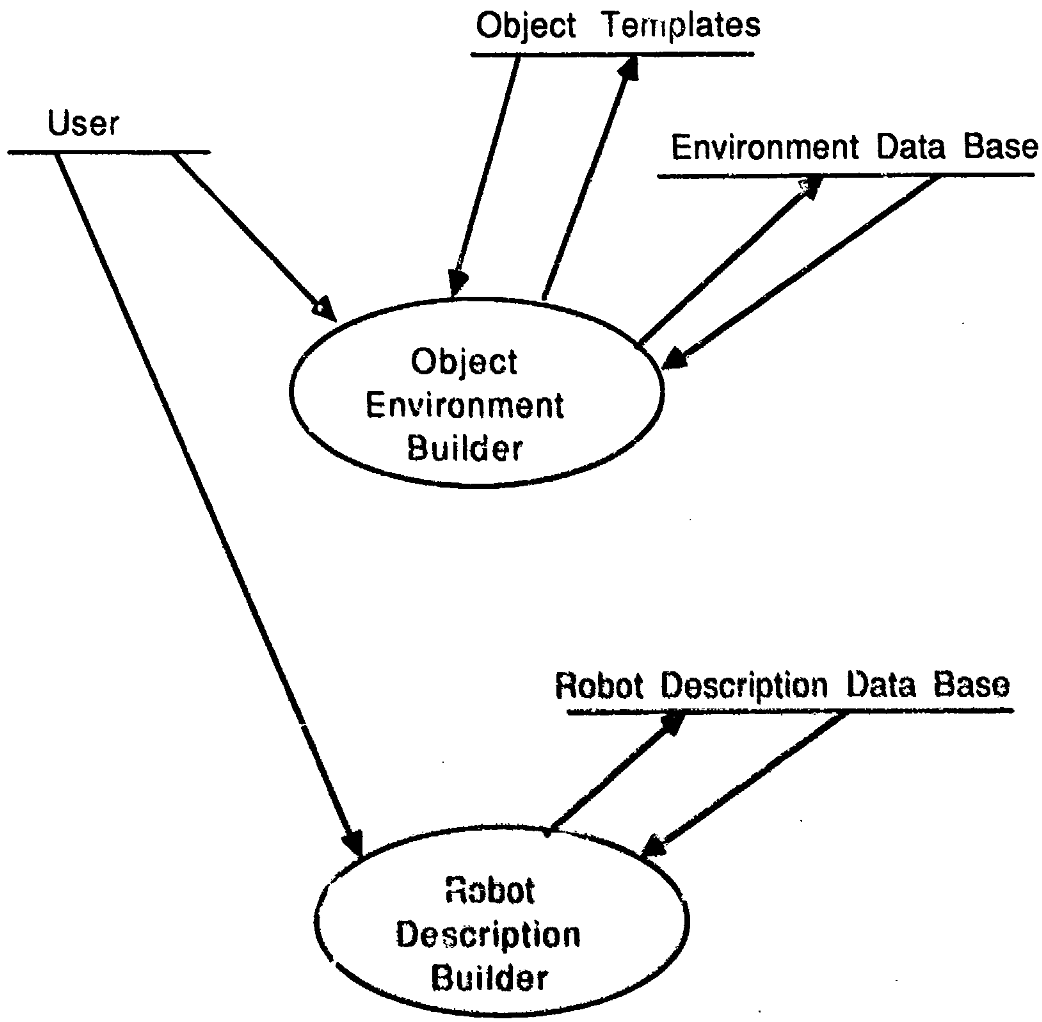

Figure 1 Data Flow Diagrams for Data Base Builders

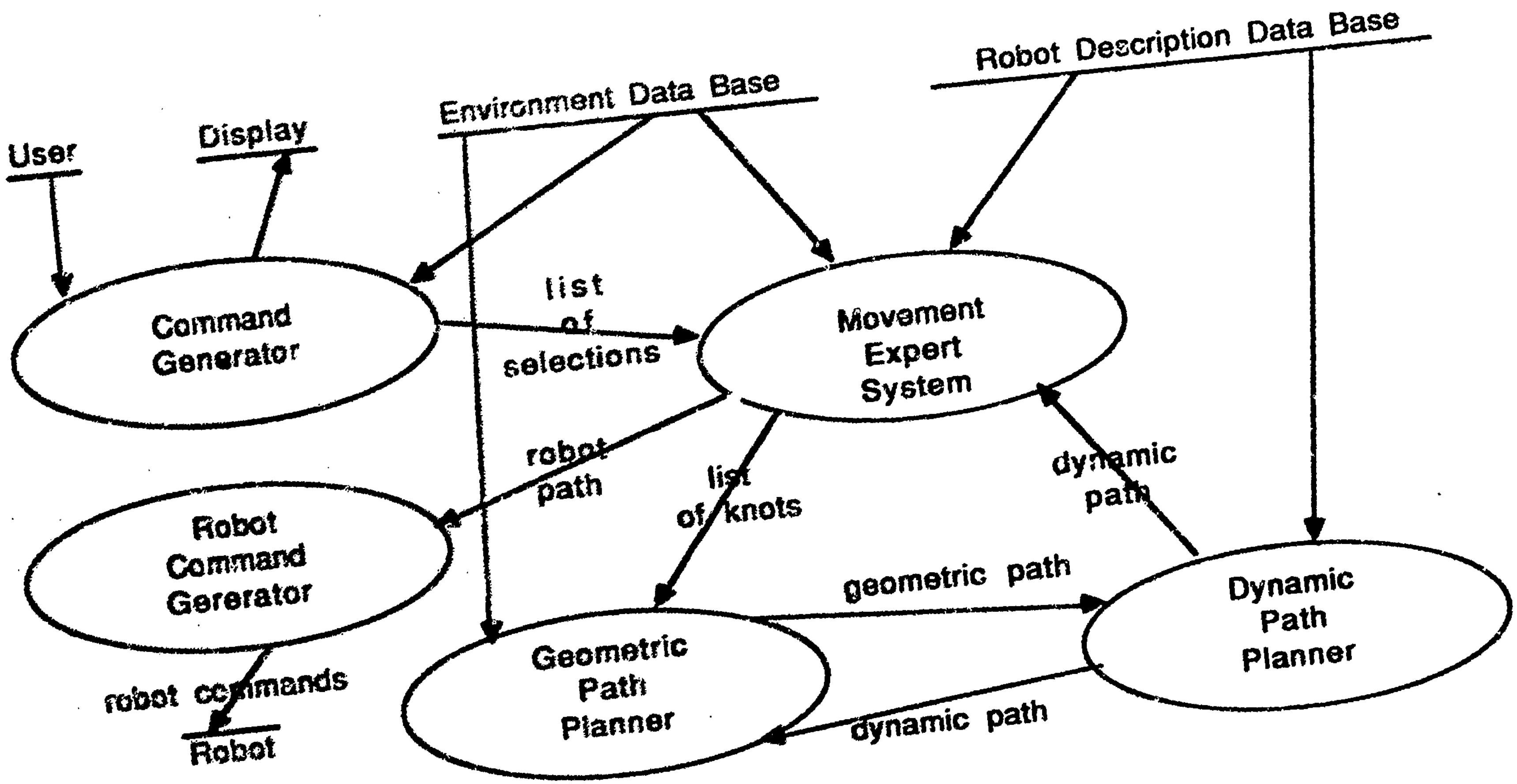

Figure 2 Data Flow Diagram of UDOMS

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Neutral File Data Exchange Between Simulators and Robots

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Abstract

Offline programming and simulator systems for robots usually create their output directly in the robot's language. This works well when only one simulator and one robot are involved. However, when multiple robots must be programmed with a single simulator or logic must be transferred between multiple simulators and/or robots, this leads to a profusion of special-purpose translators. To circumvent this problem, a general purpose neutral language was developed to carry logic between systems. This language, called Generic Descriptor Language (GDL) is the "C" language augmented by a set of robot-oriented functions. A pair of translators was developed using the UNIX lex and yacc utilities to test the feasibility of this approach.

An Overview of the Problem

When logic is developed to control robot motions using a simulator (*offline programming*), it is necessary to translate the logic from the language used to control the simulator into the language used to control the robot. This is because the simulator and robot languages are nearly always incompatible. This poses little difficulty when only one simulator and one robot are being used. However, in an integrated shop where several types of robots and simulators are used, this can easily lead to a profusion of special-purpose translators. For example, two simulator types and three different brands of robots make it necessary to maintain twenty individual translator programs (including a pair to allow logic transfer between the two simulators).[1]

The number of required translators can be reduced by the use of a neutral data transfer language. This is the same philosophy used in the Product Description Exchange Standard (PDES, formerly known as IGES, or Initial Data Exchange Standard) which is used for

Engelke, W. D. (1987) "A Generic Operations Descriptor Language for Robot Simulation," *Proceedings of the Southeastern Computer Simulation Conference*, Huntsville, —, October 1987, pp. 54 - 58a transferring geometry and notes between CAD/CAM systems. In the case of the example, this reduces the number of required translators from twenty to ten.

A format for a language and a geometry database layout have been developed which can be used for linking robots and simulators. The language is "C"-based. The language and database together are termed Generic Description Language, or GDL.[2]

A number of concerns have been raised over the years about the use of neutral file formats when translating between systems. Some of these are the following:

1. An additional language introduces extra complexity and possibility for error in the translation process.
2. Since a neutral language is inherently more general than a system-specific language, features which are individual to particular systems lose their identity when translated into the neutral language, and fail to map into their proper analogue in the target system.
3. There is extra time involved in the process, as well as a requirement that personnel performing the translation be familiar with yet another language/protocol.

While these objections are not without merit, they do not necessarily mean that the whole concept of a neutral language should be rejected; rather they indicate that close scrutiny of the situation should be performed prior to making a decision to use the method to ensure that it is appropriate. These same objections were raised when PDES was developed, and yet many major manufacturing firms (e.g. Boeing, General Motors, McDonnell-Douglas, etc.) chose to pursue a fairly aggressive implementation plan for it. This indicates that the benefits of the method can outweigh the disadvantages in certain cases.

Examples of cases where neutral file data transfer would be useful in practice include shops where multiple simulator and robot brands are used, each with its own language. Another case is that where a shop is re-hosting simulator/robot programs to allow conversion to a new system or replacement of a robot with another brand.

An interesting feature of GDL is that, since it is "C"-based, a file created in GDL can actually be compiled with a "C" compiler. Naturally, in order to do this it is necessary to supply certain key subroutines used by robot actions, such as "move" and "grasp." These supplied routines can, however, incorporate whatever logic the designer desires, and could, therefore, be used as the basis for additional simulations. For example, it would be straightforward to create a program to compute the time required to complete various robotic ...es, and then any arbitrary sequence of GDL robot moves could be timed. Subroutines ... be developed to provide outputs for other simulations such as GPSS and Network 2.5, and so on.

2 *Ibid.*

Overview of the Solution Method

The language GDL

GDL in its entirety consists of a language specification and a database layout. The language carries the logical intent of the program, and the database carries the geometry. The geometry is arranged in a hierarchical fashion to mesh well with the approach taken with many kinematics simulators. This implementation project utilized only a subset of the language specification portion of GDL. In this simple case, geometry was carried by a tag-point file as provided as output from the Deneb Robotics package.

GDL uses "C" as its basis, with a series of subroutines designed to carry out the special functions common to robots.

Subroutines for GDL

Logic is carried by subroutines named after their functions, as follows:

dmove(x,y,z,r_x,r_y,r_z) (Delta move) - Moves end effector by translation x, y, z and rotation r_x, r_y, r_z.

grasp- Activate end effector (gripper).

movehome - Move end effector to "home" position (if one is defined).

inputd(point,value) - Examine digital input point "point" and place 0 or 1 in "value."

inputr(port,string) - Accept asynchronous data through RS232-type port and place in "string."

move(x,y,z,r_x,r_y,r_z) - Moves end effector to translation x, y, z and rotation r_x, r_y, r_z (with respect to world origin).

outputd(point,value) - Place "value" at digital output "point." Valid values for "value" are 0 or 1.

outputr(port,string) - Writes the data in "string" to asynchronous output "port."

pwait(p,value) - Wait until digital input point "p" becomes "value" (0 or 1). If p=value at the time the instruction is executed, the instruction acts as a no-op.

release - Deactivates end effector (gripper).

setspeed(value) - Set maximum speed robot will use when moving between points (not including acceleration and deceleration periods).

It is possible to envision numerous other functions that may be embodied in subroutines, but these represent the most universal cross-section of robotic actions.

Translation method - lex and yacc; system to system links

The UNIX utilities lex and yacc are used to create routines for translating between systems. lex provides a lexical analyzer routine; yacc (which stands for "yet another compiler-compiler") provides translation logic routines. These two utilities do not actually perform any of the translation; rather, their output is "C" routines which can be combined and compiled. The resultant executable module will then be able to perform the actual translation. Input to lex and yacc consists of descriptions of the lexicon and syntax of the language to be translated. In this case, we are working with two sets of lex and yacc input; one to describe the translation from Deneb's simulator control software into GDL, and one to describe the translation of GDL into AML. The process for creating a lex/yacc pair to use in translation is as follows:

1. **Develop data for lex.** Describe the keywords in the input language, as well as indicating all the special characters that must be handled (such as ":;<>" and so on). Each keyword becomes associated with a "token"; character combinations which are not recognized as keywords are passed through lex's routines in accordance with character processing instructions.
2. **Develop data for yacc.** For each keyword token handled by lex, there must be a corresponding handler routine in yacc. This consists of "C" fragments which will process input data as it is encountered. There is generally heavy use of recursive symbol processing used in these descriptions to let symbols build up as they come in.
3. **Run lex.** The output will be a "C" routine, which is not usable by itself; it must be *#included* into the final routine and combined with the output of yacc.
4. **Run yacc.** The output, again, is a "C" routine. It consists of the translation logic produced by yacc to do the parsing and buildup of input data; the "C" code fragments which you have supplied are included and set up to be invoked each time their corresponding input pattern is recognized.
5. **Compile and link the "C" code into an executable module.** The resulting executable will run using standard input and output as provided by UNIX. Therefore, the

command line you key in to start the program will define the files to be input and output.

Notes about this process:

The lexical language descriptions provided as input to yacc follow a canonical language description methodology and hence fit well with language descriptions published for modern, structured languages. (Not all simulator and robot languages may be so disciplined!) Refer to Harbison and Steele, Appendices B and C, which give a LALR(1) type grammar for C.

In the case of Deneb Robotics, additional processing was provided to handle a "tag location file" which give the x, y, z, roll, pitch, and yaw values for each destination to which the robot end effector will move. For this project, this tag file was used directly. In a more complete implementation of GDL, this tag file would be converted into a hierarchical geometry database.

The process of setting up language descriptions is performed once for each simulator to be supported (here, Deneb Robotics) and once for each robotic language to be supported (here, IBM's AML). In this project, the process results in two translators; one Deneb to GDL (which we'll call Translator A) and GDL to AML (which we'll call Translator B).

Once translators have been developed for the Simulator-to-GDL and GDL-to-Robot conversions (in this case Deneb-to-GDL and GDL-to-AML), system to system translation is accomplished as follows:

1. **Develop action sequence on simulator.** This includes selecting robot end-effector positions in three-space ("tool destination points") and teaching the simulator what moves to make and actions to take. With Deneb Robotics, there may also be editing of the simulator program file to add specialized instructions that are not generatable through mouse pokes.

2. **Exit simulator to UNIX; translate simulator program to GDL.** In this case, translation from Deneb data to GDL is performed using Translator A.

3. **Translate GDL to robot language.** Translation from GDL to AML is performed using Translator B. Examples 1 through 3 show the process of conversion (see next page):

Example 1a: Deneb Robotics GSL Simulation Language for very simple program. Odd numbers for coordinates are due to round off error in the simulator.

```
program p20
-----------------------------------------------
VAR
tp1, tp2, xp1, tp3, tp4:      POSITION
-----------------------------------------------
begin
    move to tp1
    move to tp2
    grab xp1 at link4
    move to tp1
    move to tp3
    move to tp4
    release xp1
    move to tp1
    move to tp3
    move home
-----------------------------------------------
end p20
```

Example 1b: Tag file giving coordinates of tag points in simulation

```
TAG: tp1
    -0.00265667 399.948 259.964 0 0 0
TAG: tp2
    -0.00319223 399.948 159.979 0 0 0
TAG: tp3
    -434.979 -2.99345 259.959 0 0 -89.9994
TAG: tp4
    -434.980 -2.99413 159.974 0 0 -89.9994
```

Example 2: Above simple program converted from GSL to GDL

```
/* ---- Source GDL generated from Deneb Robotics ----*/
double tp1[6] { -0.00265667, 399.948, 259.964, 0.00000, 0.00000, 0.00000},
    tp2[6] { -0.00319223, 399.948 ,159.979, 0.00000, 0.00000, 0.00000},
    tp3[6] { -434.979, -2.99345, 259.959, 0.00000 ,0.000000, -89.9994},
    tp4[6] { -434.980, -2.99413, 159.974, 0.00000, 0.000000, -89.9994} ;
/* ----------------------------------------------------------*/
main()
    {
    move(tp1);
    move(tp2);
    grasp();
    delay(1000);
    move(tp1);
    move(tp3);
    move(tp4);
    release();
    move(tp3);
    movehome();
/* ----------------------------------------------------------*/
/*--- end of generated GDL source --- */
```

Example 3: AML source generated from above GDL source. Note that several coordinates are intentionally left out because the robot supports only X, Y, Roll, and UP/DOWN.

```
----------------------------------------------------------*/
tp1: NEW PT ( -0.00265667, 399.948, 0.00000);
tp2: NEW PT ( -0.00319223, 399.948 ,0.00000);
tp3: NEW PT ( -434.979, -2.99345,  -89.9994);
tp4: NEW PT ( -434.980, -2.99413,  -89.9994);
----------------------------------------------------------*/
-- SOURCE FROM GDL/AML TRANSLATOR
AMLPROG: SUBR;
PMOVE(TP1);
DOWN;
GRASP;
UP;
PMOVE(TP3);
DOWN;
RELEASE;
UP;
PMOVE(650,0,0);
END;
```

Specialized Techniques Used in this Protocol

The very idea of introducing a neutral language into the process of translation sometimes produces dread and loathing on the part of robotics software people, because they envision much extra complexity and difficulty in accomplishing the translation. As it turns out, this particular combination of languages (Deneb-AML) results in a very straightforward and readable set of routines. However, note also that AML-Entry for the IBM 7535 provides a very limited subset of the functions of which robot controllers in general are capable, and this project was a subset even of that. Therefore, a rigorous test of the GDL method would need to include a more complex robot language as its target to be able to draw generalized conclusions about the utility of GDL. However, even with this small test, some interesting points became apparent:

Deneb to GDL: The translation routine has to handle tag point locations and generate array initializations. These arrays (which then become variable names in C) are given names corresponding to tag point names. Conceivably, the user could disrupt the validity of the GDL routines by giving tag points names which are reserved words in C! This could happen in other ways when using Deneb Robotics also, as there is frequently the need to embellish the logic in the simulation program with manually entered code.

Use of GDL routines: Since GDL routines are in "C," they can be compiled with any C compiler. Routines must be provided, with their names corresponding to robot functions as already mentioned. However, by supplying routines (for these robotic actions) which perform other related specialty functions (not just robotic moves), a number of useful studies could be performed, such as visual simulations of various types (depending on the type of system) collision detection, timing simulation and production of output for other simulation programs such as GPSS. Code in "C" can also be analyzed with standard C optimizers and the UNIX program "lint" which checks for bugs.

GDL to AML: Conversion of GDL to AML turned out to be one of the more difficult parts of this project, because translation is not as simple as just describing GDL to yacc. The problem here is that there are a number of machine-specific issues which must be overcome. The major problem is the extremely limited nature of AML-Entry for the IBM 7535 robot. The machine supports only two Z positions for the end effector: UP and DOWN. Since the Deneb Robotic simulator program allows one to move the Z position with abandon, code had to be developed consistent with yacc's processing method to keep track of changing Z coordinates and then generate correct UP or DOWN commands in AML.

Summary of Conclusions

It was determined that conversion to C could be useful for more things than just translation: many useful additional studies could be performed on robotic logic by converting it into compilable C. Developing translators is not a particularly difficult task once one gets over the learning curve of understanding how to use lex and yacc. Each robot controller poses its own challenges to the translator developer, ranging from slight (for powerful, structured languages like GMF's Karel) to intimidating (for machine-level codes required by Cincinnati Milacron).

Simulator-to-simulator links are possible. An example would be a case in which it is desired to move extensive libraries of routines from, say, McDonnell-Douglas PLACE format into Deneb Robotics. Study would have to be undertaken as to how to map the languages from one to the other. However, it is expected that loss of intelligence would occur primarily at the target system, as the "C" language is general enough to represent almost anything (assuming appropriate subroutines). Robot to robot links are possible also, for example moving a library of movement routines from a robot being scrapped out to a new replacement.

From a practical standpoint, the complexity of this method is such that it is probably best reserved for special cases, such as many-vendor sites and studies of critical robot applications such as space-based and military systems.

Acknowledgements

UNIX is a trademark of Bell Laboratories. The keywords "lex," "yacc," and "lint" are names of utility programs supplied with UNIX.

IBM, AML, and AML-Entry are trademarks of International Business Machines Corporation.

Deneb and Deneb Robotics are trademarks of Deneb Robotics, Troy, Michigan.

PLACE is a trademark of McDonnell-Douglas Corporation.

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Cooperating Expert Systems

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Abstract

The number and variety of computer systems one is likely to find in any modern space or military system will be great. In a very real sense the computer systems in such a project will form a committee of experts. As in any committee, it is important to take steps to facilitate the cooperation of the experts. This paper will focus upon the cooperation of multiple expert systems.

A cooperation assistant will be proposed as a means of controlling this inter-expert system communication. Such an assistant will itself be an expert in the functionalities of and the protocols between the various experts in its domain. It will contain meta-knowledge about the structures and needs of these experts and will be able to use this knowledge to coordinate their activities.

Introduction

In [1] the authors provided the motivation for inter-expert cooperation as a systems design consideration and proposed an Expert Systems Cooperation Paradigm to categorize the various types of interaction. In this paper we would like to discuss the possibility of a Cooperation Assistant (CA) responsible for managing these interactions. The CA will be responsible for routing all expert system (ES) input and output and resolving any conflicts that might occur. We will begin by categorizing the ES's in question and proceed to describe a message passing facility based on a blackboard architecture [2]. We will then be able to define the charter of the CA and discuss some of its more interesting duties. Finally, the utility of the CA will be demonstrated via an example.

ES Category

Many types of ES's have been proposed for monitoring and controlling complicated electrical, chemical, and mechanical systems [3]. There has been a great deal of interest especially in the areas of diagnosis and scheduling [4]. For the purpose of the current discussion, we would like to simply divide these ES's into those that monitor a physical system, those that control some aspect of a physical system, and those that do both.

ES Category I

The majority of the intelligent systems in use today fall under the first category. All pure fault diagnosis and prediction ES's are designed to monitor and interpret sensory data in an attempt to isolate and find justification for any irregularities. In general they do not, however, act on their conclusions. A scheduler has a similarly passive approach. They usually suggest a sequence of events, given the tasking requirements and resource constraints, but do not actually administer the schedule.

ES Category II

ES's that are responsible for actually controlling a physical system are less common. Repair ES's and the general category of control systems do change their environment. Such systems must be extremely reliable and predictable.

ES Category III

The authors believe that the third category, those ES's that both monitor and control a physical system, should be avoided if possible. This is what is referred to as a closed loop: a computer system that has complete responsibility for some system in that it can detect, interpret, and correct any problems. Although intelligent systems may prove valuable in such applications, the task should be broken down into more manageable components. As will be evident in our discussion of the CA, a network of ES's with limited, well-defined duties will be more reliable.

The Blackboard Architecture

A blackboard, as described in [2] is a method of centralizing communications among a set of computer systems. In our case, the blackboard will serve as an input/output buffer between the CA and the ES's. Each ES will have a particular section of the blackboard with which to communicate. The CA will have access to all sections of the blackboard, but each ES will be limited to its own area. Also, there will be no direct communication links between ES's. In this manner, the blackboard will serve as a controlled access, centralized communications area.

The analogy in our case is little different than the one usually given to explain blackboard architectures. Suppose we allow a group of people to talk to one and other only by writing their messages on the small blackboard we have given each of them. With this restriction they are given a task which will require them to communicate. No one may look at any blackboard other than his/her own. One member of the group, the coordinator, however, is is allowed to read and write on any blackboard. This person's responsibility then is to relay any messages to their appropriate destinations. As we shall see, the coordinator might also try to monitor the group's progress by noting the messages as they pass by and detecting any conflicting messages. For example, if one of the group members has a distorted view of the state of the task, the coordinator will be best able to notice this by comparing that person's messages to those of the others.

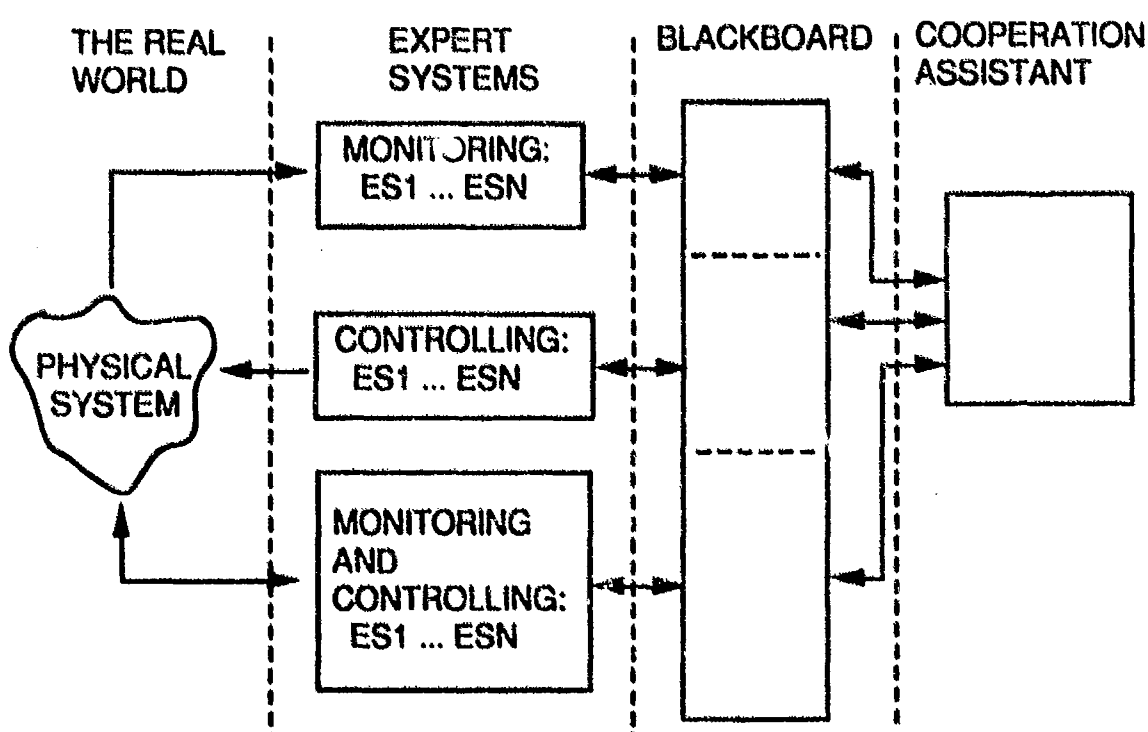

Fig 1. System Schematic

The Communications Assistant

The above discussion brings us to the point where we can define the duties of the CA. Fig. 1 shows a schematic diagram of the system as it has been described so far. Note that no ES can communicate another accept through the blackboard and, by extension, the CA. Fig. 2 shows a more detailed view of the CA.

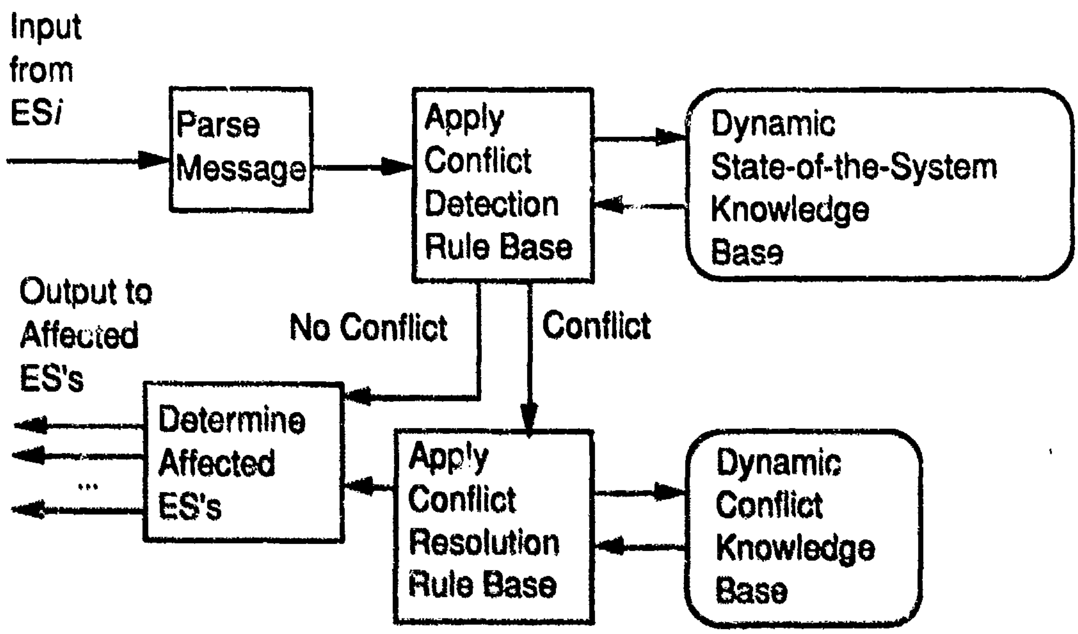

Fig 2. The Cooperation Assistant

The CA will have four main responsibilities: routing messages, detecting message conflicts, resolving these conflicts, and maintaining a log of all communications. The message routing and log maintenance should be straight forward matters, so we will concentrate here on the conflict resolution portions.

The Conflict Detection (CD) Rule Base

The CA will contain a Conflict Detection rule base that will be used to compare in-coming messages to the current State-of-the-

System knowledge base in search of inconsistencies. This rule base will capture meta-knowledge pertaining to the ways in which the inputs and outputs from the various ES's should compare. It's rules will be designed so as to detect an aberrant message from an ES in much the same way any diagnosis ES searches for inconsistent readings. In this sense, the CD is really a meta-ES, that monitors the other ES's as they do the physical system.

The Conflict Resolution (CR) Rule Base

If the CD finds something in an incoming message that conflicts with the current State-of-the-System knowledge base, it will proceed to the CR rule base which will try to decide which ES is right and which is wrong. This rule base will be designed to determine whether the in-coming message is indeed the aberrant one or if the State-of-the-System knowledge base is in error. The CR will take into consideration the Conflict knowledge base which contains a history of past conflicts.

An Example Message

Suppose we have an ES called PUMP7-ES that is responsible for monitoring PUMP7 and an ES called TANK2-ES that monitors TANK2. Also suppose that the output from PUMP7 flows through VALVE345 and into TANK2. Now, PUMP7-ES puts the following message in its portion of the blackboard,

```
(PUMP7-ES:TEMPERATURE-OUT 112)
```

Once the CA parses this message it passes to the CD which might contain the following rule,

```
(IF (> (TEMPERATURE-DIFFERENCE (PUMP7-ES:TEMPERATURE-OUT)
                               (TANK2-ES:TEMPERATURE-IN))
       10)
   (THEN (SIGNAL-CONFLICT 529)))
```

If, according to the current State-of-the-System knowledge base, TANK2-ES:TEMPERATURE-IN is greater than 122, the message will be passed to the CR knowledge base. The rules in the CR are a little trickier. One might look something like this,

```
(IF (> (STANDARD-DEVIATION PUMP7-ES:TEMPERATURE-OUT)
```

```
   5)
 (THEN (DECREMENT-CERTAINTY-FACTOR
        PUMP7-ES:TEMPERATUE-OUT
         0.5)))
```

And, if TANK2's in-temperature should be more stable, there might be a rule like this,

```
(IF (> (STANDARD-DEVIATION TANK2-ES:TEMPERATURE-IN)
   2)
 (THEN (DECREMENT-CERTAINTY-FACTOR
         TANK2-ES:TEMPERATUE-IN
         0.5)))
```

Through rules like these, the CR would try to determine whether PUMP7-ES's message is wrong or if TANK2-ES's perception of its in-temperature is wrong. If neither of them seems to be misbehaving in any other respect, it might decide that there is a problem with VALVE345 or some component near it.

In any case the CA must lastly decide which of the other ES's (perhaps a repair ES) need to be given a messages.

Conclusions

As we have seen, the CA will act much like an upper level manager who gets reports from his department heads. Like the CA, he reads the reports he gets and send out memos to those departments which are affected. If the report was from shipping saying that they didn't have enough to do, he might send a memo to the production and finishing departments saying to get on the ball. Or, if his files on the shipping department show a lot of complaints, he might send a memo back to them saying that they might want to take the time to do a better job.

The CA is best thought of as two meta-ES's, the CD and CR. Note that they are the only ES's allowed to communicate directly with one and other. This is necessary given the nature of their tasks. The CD is a category I ES that monitors the other ES's via the blackboard . The CR is a category II ES in that it's decisions might actually affect the other ES's.

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Space Languages--
Solving the Classic Scheduling Problem in Ada and Lisp

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ABSTRACT

The comparison of programming languages is best seen while evaluating similar systems. This paper will investigate the strengths and weaknesses of both languages as the scheduler is being implemented. Some features used in both languages shall be object-oriented paradigms, parallel programming, search and production heuristics, and other classical AI implementations.

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A SYSTEM FOR HIGH RESOLUTION 3D MAPPING USING LASER RADAR AND REQUIRING NO BEAM SCANNING MECHANISMS

1 June 1988

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ABSTRACT

Present optical systems designed to gather 3D data over broad fields of view use raster scan techniques to move a narrow transmit beam and the receiver field of view over the region of interest. This requires delicate mechanical scanning devices and relatively long data acquisition times to map the region. Data distortion under dynamic conditions is inherent, and the system is prone to detection by hostile sensors. A system concept is proposed which, through the use a single laser transmitted pulse and multiple optical receivers with nc moving parts, largely eliminates the above deficiencies.

I. INTRODUCTION

Complete 3D data over a broad angular field of view and depth of field can be gathered based upon the reflections from a single transmitted laser pulse. No mechanical scanning is required and the data represents a true 3D "snapshot" of the subject scene. Covert operation is enchanced as a result of the sparse laser transmissions required. The eye safety characteristics of the system are also enchanced. The absence of delicate scanning mechanisms provides an inherently more rugged design. The 3D data acquisition rate for the system is approximately 150 times greater than that of a typical scanning system.

Proprietary coding of optical shutters in each of the multiple optical receivers permits the number of such receivers to be reduced to a very practical few. An alternative configuration of the system reduces the number of receivers required to one, at the expense of increased data acquisition time. In such a configuration, equivalent data can be gathered by transmitting and processing reflections from a small number of laser pulses - this number being equal to the number of receivers in the multiple receiver configuration.

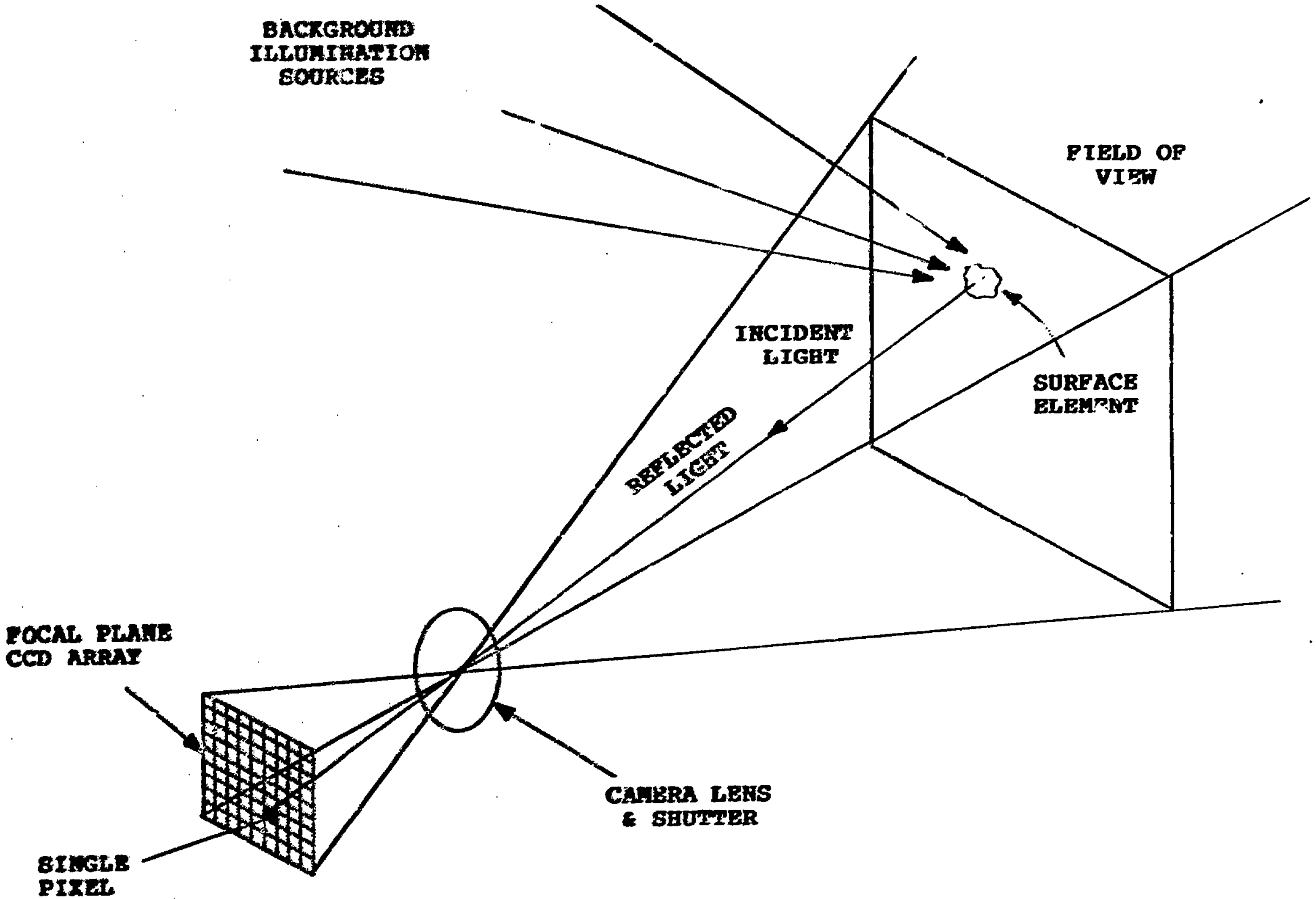
This new sensor concept (LORDS) has potential application to a broad range of target or scene analysis problems, both in the near and long term.

II. DESCRIPTION OF THE LORDS CONCEPT

The LORDS system configuration and its operation can be best described by sequentially building on the basic concepts of a 2D camera and range discrimination techniques associated with radar principles.

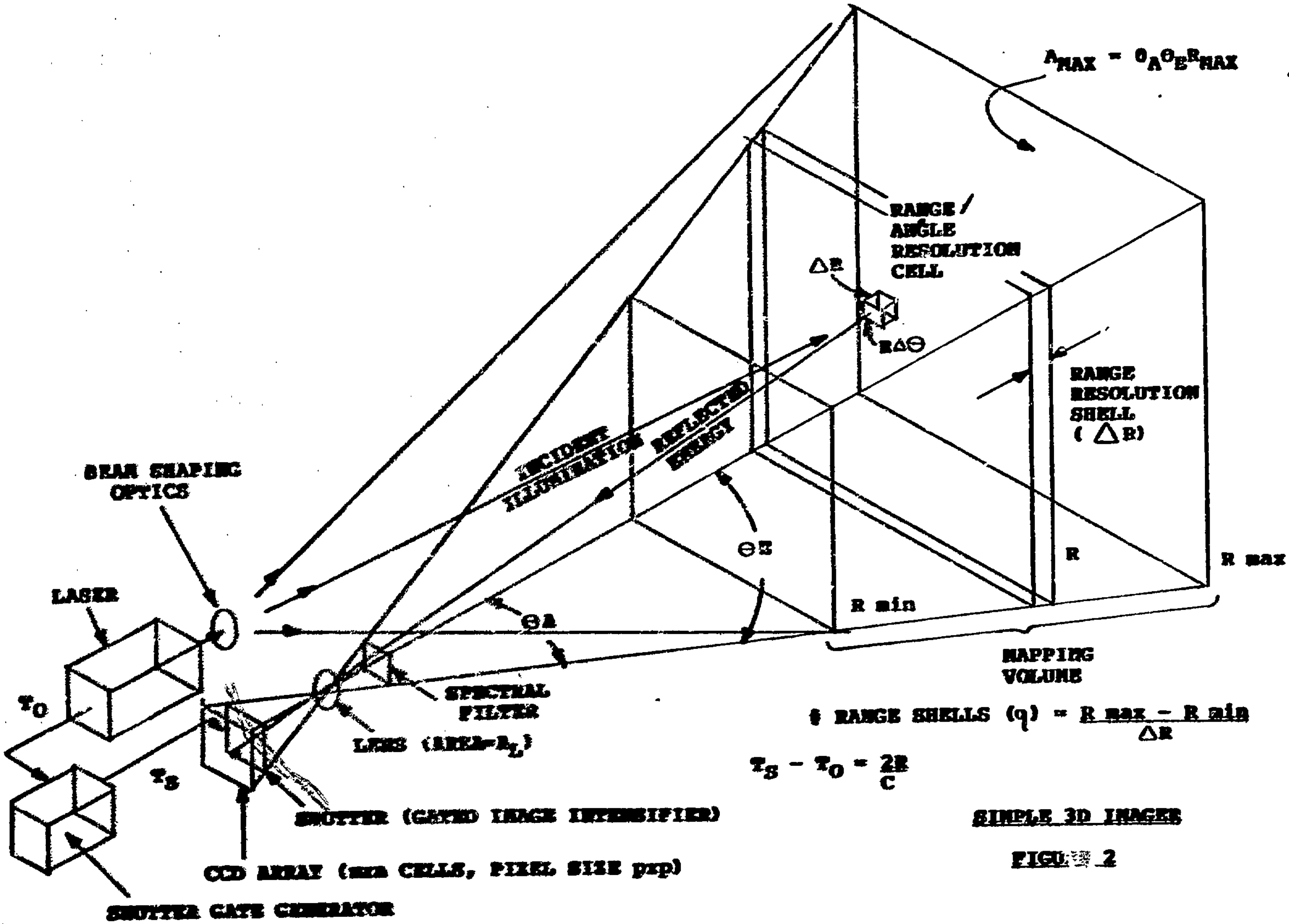
Clearly, the simple 2D camera shown in Figure 1 will provide an image of the scene within its optical field of view. Light normally reflected from objects or surfaces within the scene is focused on the image plane of the camera. The source of this illumination is normally provided by background light originating from the sun, moon or stars or otherwise by man-made light sources. This illumination is constant during the time when the camera's shutter is open. The total light energy focused on each small pixel of the image plane is proportional to the reflected light level from that portion of the scene (corresponding to that pixel) integrated over the shutter open time. The 2D light image thus recorded provides high angular resolution but no information as to the distance (range) of the object surface from the camera.

Assume, for the moment, that all above background illumination is eliminated and, in its stead, the scene is illuminated only by a short impulse of light transmitted at the camera location at time To. If the camera shutter is opened for only an equally short impulse at a time Ts (after To), then light reflected from the scene will be captured on the camera's image plane only for surfaces within the scene lying at a specific distance from the camera. This distance (range) is that which provides a round trip delay time at the speed of light equivalent to Ts - To. Thus, light focused on any pixel indicates that a surface exists at that range and in a direction defined by the pixel location on the image plane. A true 3D image is thus implemented, sensitive however only to surfaces lying at a specific distance from the camera. By transmitting multiple light impulses and sequentially incrementing the camera shutter open-



SIMPLE (2D) CAMERA

FIGURE 1



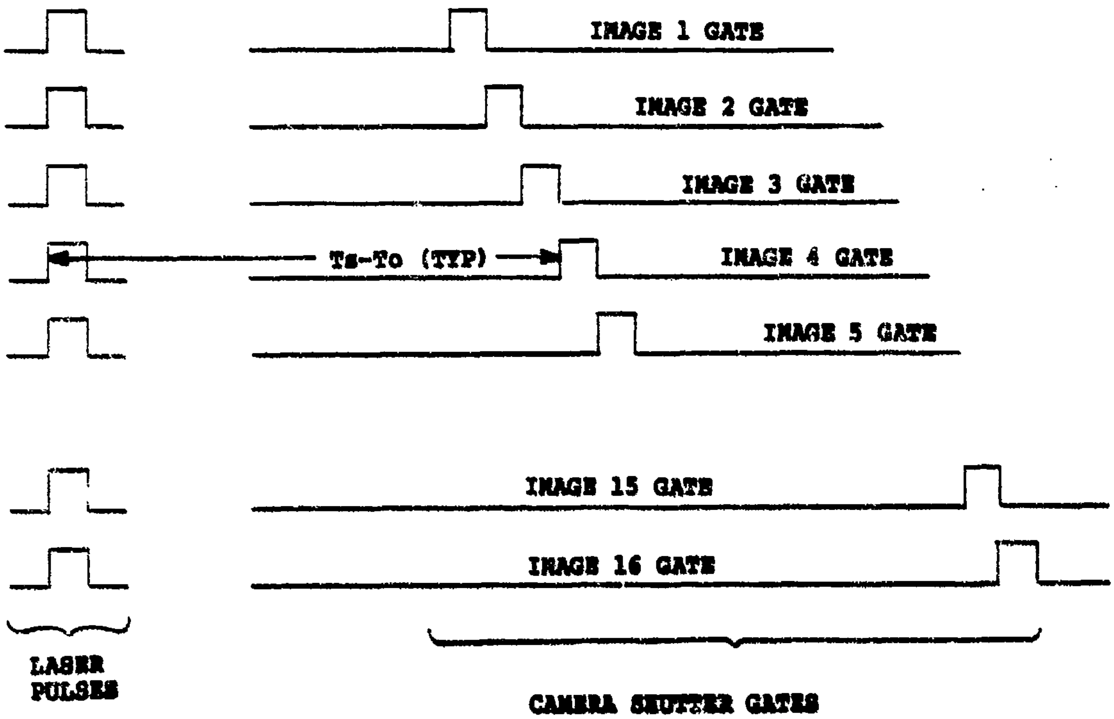
SIMPLE 3D IMAGER

FIGURE 2

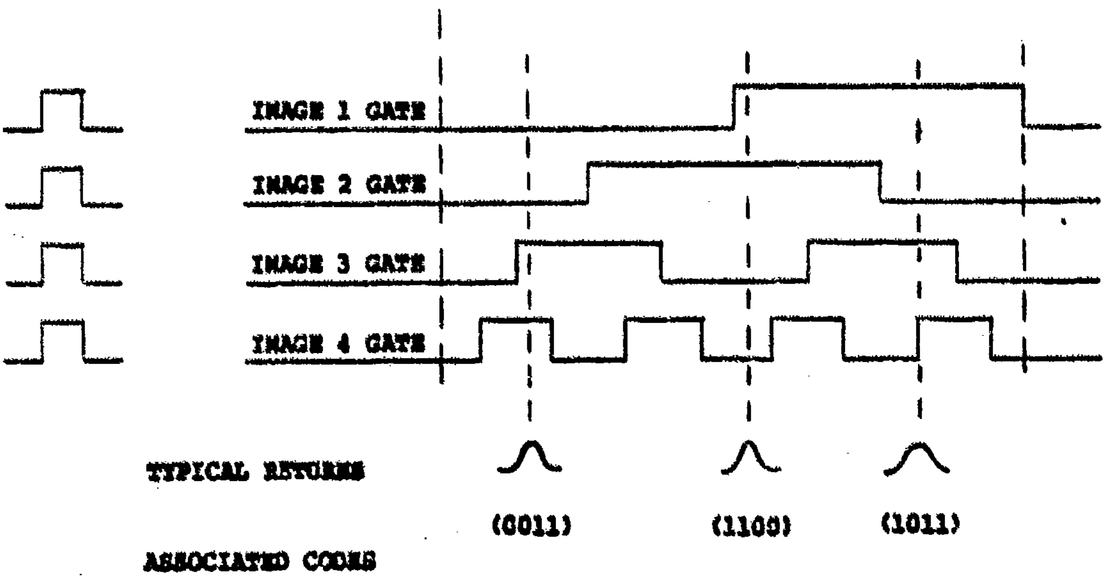
ing time with respect to the transmitter impulse time, a sequence of images is formed, each of which represents the angular direction to surfaces in the scene at sequentially increasing ranges. Such a system is shown in Figure 2. The transmitted impulse is laser generated with narrow spectral width and the optical filter in the receive optics is centered at the transmitted wavelength. This filter serves to reduce the effects of interfering broadband background illumination on system performance.

The system thusfar described requires that, for a mapping of q resolution cells in range, q illuminating impulses be transmitted and q corresponding images be formed. Available camera CCD arrays require 1/60th of a second to be read and stored for analysis. With this limit on image capture time, it will require q/60 seconds to gather all of the 3D data from the scene. Thus, for a reasonable number of range resolution cells, at least several seconds are required to gather all data. During this period of time, the scene must remain relatively unchanged and the relative position of the scene with respect to the sensor system must be relatively stable. If not, the mapped data will be unavoidably distorted. Fortunately, means are available to significantly reduce this data acquisition time. These methods are the essence of the LORDS concept.

The typical sequence of illuminating impulses and camera shutter gates for the previously described system is shown in Figure 3a. For illustrating simplicity, it is assumed that only 16 (q = 16) range resolution cells are to be mapped, thus 16 images are to be formed. A scene surface at any specific range will appear in one (or at most 2) of the 16 images formed, and at a pixel location(s) according to its angular direction and extent with respect to the camera boresight. In Figure 3b, a more efficient means of gating the camera shutter is shown which requires only 4 illuminating impulses and effects the same result as above. Here, the shutter is gated by the 4 waveforms shown which together form a 4 bit binary coded representation of the 16 states shown in Figure 3a. In this case, a scene surface at any specific range will appear in 1, 2, 3 or all 4 images and in an order dependent on its range. Some typical examples are shown. The pixel positions within these images are still dependent only on the angular direction to the surface. Analysis of the 4 images will provide the same inherent data as the previous 16, given a little added



SEQUENTIAL GATING SEQUENCE
FIGURE 3a



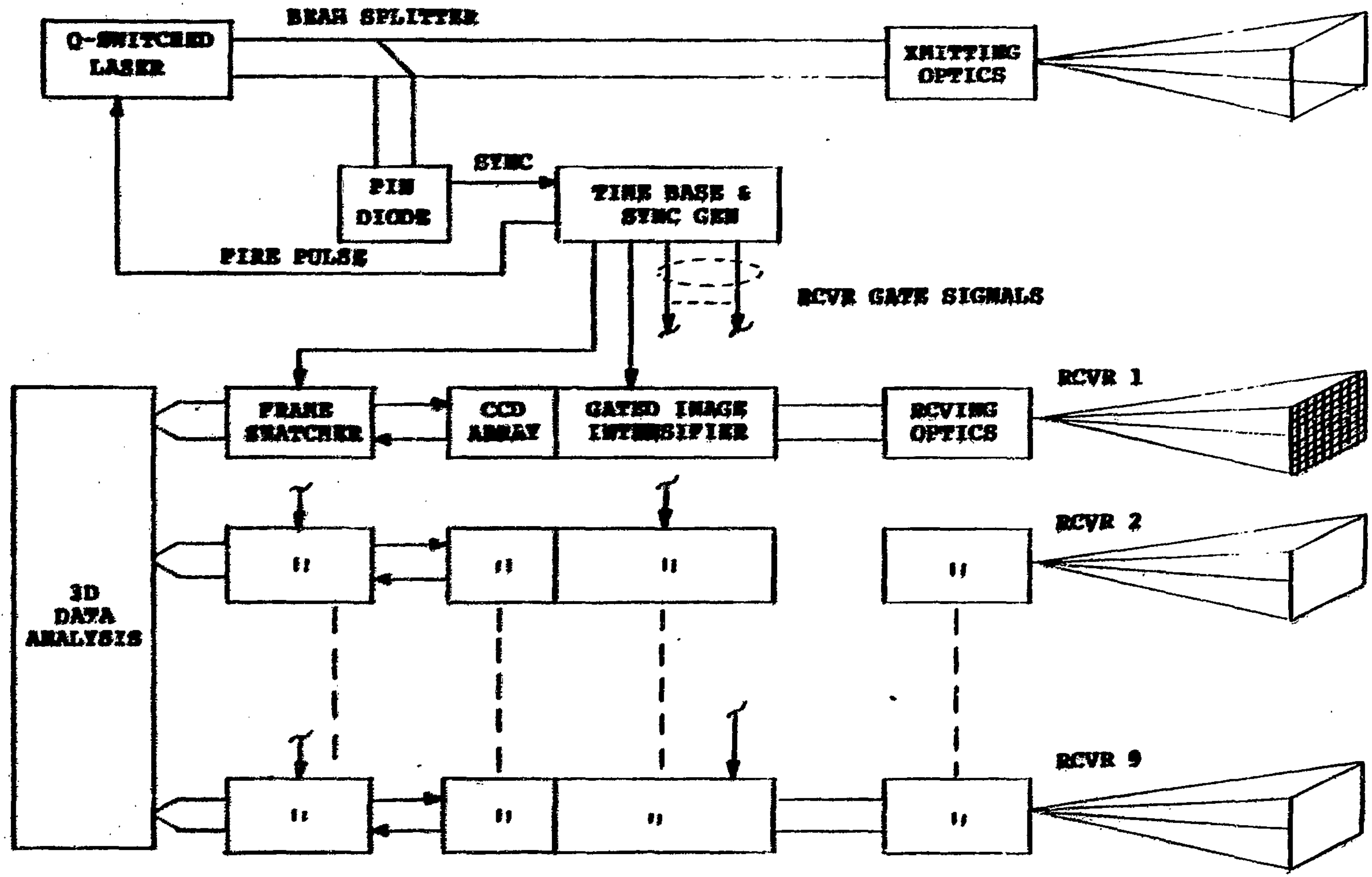
CODED GATING SEQUENCE
FIGURE 3B

processing time to decode the data. What is conceptually important is that with these methods, total data acquisition time can be substantially reduced. For instance, if a pure binary coded gating sequence could be used and 512 range resolution cells were to be mapped, only 9 illuminating impulses and corresponding shutter gating waveforms need be used. This represents a reduction in data acquisition time by a factor of almost 57. For an image capture time of 1/60th of a second, the complete 3D image data can be captured in 150 milliseconds.

While this capture time may be adequate for many applications, it may still be insufficient to gather distortion free data on dynamically changing scenes or from rapidly moving sensor platforms. However, a true "snapshot" capability can be realized by adding hardware to the system. By providing a multiplicity of receiving optics, shutters and cameras (for instance 9 parallel receivers for 512 range resolution cells) all required data can be gathered based upon the reflections from a single transmitted laser impulse. Such a system is shown in Figure 4, and is the ultimate implementation of the LORDS concept. Here, a single laser transmitter and 9 identical optical receivers are arranged with their optical boresight axes parallel and as nearly colinear as physical constraints allow. Each receiver shutter is gated with a different waveform, each synchronized to the single laser transmission pulse. The combination of these 9 waveforms form a 9 bit binary code which unambiguously defines the 512 range resolution cells to be mapped. Each receiver provides a single image. Analysis of the 9 total images will provide the complete 3D data for the scene to be mapped. If camera focal plane arrays of 512 x 512 pixels are used (for instance) a mapping volume of 512 x 512 x 512 resolution cells can be achieved. Data acquisition time is essentially the round trip delay time to the maximum range of the mapping volume (i.e. 10 microseconds at 1500 meters). Thus, the scene is truly taken in "snapshot", and distortion is eliminated.

III. SYSTEM IMPLEMENTATION RESTRICTIONS

The ability to implement a practical system employing the above described concepts is presently limited by availability of several critical components.



TYPICAL LORDS SYSTEM

FIGURE 4

Foremost of these are the following:

1. Narrow pulse high energy laser transmitter for scene illumination.
2. High speed electric shutters for the camera.
3. Reasonably large CCD photosensitive arrays for image capture at the camera focal plane(s).

Large focal plane arrays of high sensitivity presently exist only for the visible light spectrum (below 1 micron). To achieve range resolution capabilities of 1 meter (for instance) the generated laser pulse width and corresponding shutter gate times must be 5 nanoseconds. Correspondingly faster operation is required for better resolution. A high speed electronic shutter can be realized by gating an image intensifier consisting of a photocathode to convert incident photons to free electrons which are then multiplied by a microchannel plate and then strike a phosphor screen. Here the electrons are converted back to photons, which in this application, are received by the CCD array. Photocathode material of high quantum efficiency (to provide the required optical sensitivity) is available only in the visible light portion of the spectrum. Thus, present component availability restricts a LORDS type system to operation in the visible spectrum. As such, its performance potential is inherently limited by background interference from solar radiation and optical attenuation in adverse weather conditions. Accepting these restrictions, system capabilities are further subject to the ability to generate high energy laser illuminating pulses to sufficiently compete with solar radiation interference and "burn through" the atmospheric attenuation associated with adverse weather. The following section provides some insight into system performance which can be achieved with presently available component capabilities.

IV. SYSTEM PERFORMANCE POTENTIAL

The ability of the system to provide accurate 3D data requires that sufficient optical energy can be focused on the image plane(s) as a result of the laser illuminating pulse. This energy must be sufficiently greater than that from normal background illumination and inherent system noise so that proper and accurate image decoding can take place. Computation of this available energy is presented as follows:

Referring to Figure 2, energy reflected from any surface lying within the inspection volume will be imaged on one or more pixels at the focal plane of the camera. A general m x n pixel array is shown. The inspection volume is thereby subdivided into m x n corresponding angular resolution cells. This volume is shown to be further subdivided into q range resolution cells extending from the minimum inspection range (Rmin) to the maximum inspection range (Rmax). The inspection volume is illuminated evenly over its angular extent by the transmitted laser pulse. This can be achieved by employing 2 orthogonal cylindrical lens to spread the transmit beam into a nearly rectangular pattern matched to the cameras' field of view (θ_A , θ_B). The following computations apply for each of the optical receivers of the LORDS system..

The illuminating energy density at any range (R) within the volume is:

$$\frac{E_T}{\theta_A \theta_E R^2} \qquad \text{Joules per square meter}$$

where E_T is the total energy of the transmitted laser pulse and the denominator is simply the total area at range R over which this energy is spread. The total energy passing through any resolution volume is therefore:

$$\left(\frac{E_T}{\theta_A \theta_E R^2}\right) (R\Delta\theta)^2 \qquad \text{Joules}$$

where $(R\Delta\theta)^2$ is the lateral area of the resolution cell in square meters at range R. We will presume that any surface intersecting this resolution volume is a Lambertian scatterer with reflectivity r at the transmitted optical wavelength, and whose surface normal lies at an angle ϕ with respect to the direction to the sensor. The total energy reflected from this surface back towards the camera is therefore:

$$\left(\frac{E_T}{\theta_A \theta_E R^2}\right) (R\Delta\theta)^2 \left(\frac{r \cos \phi}{\pi}\right) \qquad \text{Joules per steradian}$$

where the third term above is that derived from Lamberts' law of reflectivity.

Of this reflected energy density, that captured by the cameras' receiving aperture and focused on the corresponding pixel in the image plane is:

$$\left(\frac{E_T}{\theta_A \theta_E R^2}\right) (R\Delta\theta)^2 \left(\frac{r \cos \phi}{\pi}\right) \left(\frac{A_L}{R^2}\right) \quad \text{Joules}$$

where the final term represents the solid angle subtended by the camera lens area A_L at range R. Thus, the total energy E_p which arrives at each pixel is expressed as follows:

$$E_p = \left(\frac{E_T}{\theta_A \theta_E R^2}\right) \left(\frac{r \cos \phi}{\pi}\right) A_L \ (\Delta\theta)^2 (L) \quad \text{Joules}$$

where the final term L reflects all system losses such as losses in transmitting and receiving lenses, optical filter losses, atmospheric transmission losses and unavoidable spillover of the transmitted beam pattern beyond the cameras' angular field of view. For the worst case of energy reflected from surfaces lying at the maximum range of the inspection volume, the above expression can be transformed into a more useful form via the following identities:

$\theta_A \theta_E R_{max}^2 = A_{max}$ (the area viewed by the camera at the rear of the inspection volume)

$A_L = \frac{\pi}{4} \frac{f^2}{(f\#)^2} =$ (where f and f# are the focal length and f number of the receiving lens)

$\Delta\theta = \frac{p}{f}$ (where p is the lateral dimension of a pixel in the focal plane)

Applying these identities:

$$E_p = \frac{E_T}{A_{max}} \ \frac{r \cos \phi}{4} \ L \ \frac{p^2}{(f\#)^2} \quad \text{Joules} \qquad \underline{\text{EQ 1}}$$

The minimum required energy per pixel for a detection probability of P_D is given below:

$$E_{min} = \frac{hc}{\lambda\eta} \ \ln \ (1 - P_D)^{-1}$$

where: h = Plankes constant (6.624×10^{-34} joules sec)

c = the speed of light (3×10^{8} meters/sec)

λ = optical wavelength (assumed 0.5 microns)

η = quantum efficiency of microchannel plate photocathode

The received energy is focused on the photocathode of the image intensifier. In the visible portion of the spectrum, photocathodes are available with quantum efficiencies of 20%. Thus,

$$E_{min} = 2\times10^{-18} \ln (1-P_D)^{-1} \quad \text{Joules}$$

where P_D is the required detection probability at each pixel for all of the multiple LORDS cameras. If the LORDS system uses N cameras and each of the N image planes consist of m x n pixels, then an error free 3D snapshot requires correct detection in m x n x N pixels. Any single detection error will create an error in range position in one angular resolution cell. If we arbitrarily take this as acceptable performance, then the required detection probability per pixel (P_D) is such that:

$$1 - P_D = \frac{1}{mnN} = \text{probability of 1 error}$$

therefore:

$$E_{min} = 2 \times 10^{-18} \ln (mnN)$$

Equating this to the received energy per pixel from EQ 1 and solving for the required transmit energy:

$$E_T = (8 \times 10^{-18}) \frac{(f\#)^2}{(p)^2} \left(\frac{1}{r \cos \phi}\right) \left(\frac{1}{L}\right) (\ln mnN)\, A_{max}$$

To compute the required transmit energy, the following parameters are assumed:

r cos = .1 (worst case target reflectivity)

$f\# = 1.2$

$p = 50$ microns (typical of CCD arrays)

$m = n = 512$ (providing 512 x 512 angular resolution elements)

$N = 9$ (providing 512 range resolution elements)

$$L = \frac{1}{4} \; e^{-\left(7.8 \; \frac{R_{max}}{V}\right)}$$

The loss term (L) assumes 6db of optical losses in the system itself, with the exponential term accounting for the total round trip atmospheric attenuation due to scatterers (fog, haze, rain, etc.) at the maximum range Rmax and for a visibility V. The latter is defined as the range at which the contrast between an object and the background is decreased by 98% from that in clear weather.

Applying these parameters, the transmit energy required is:

$$E_T = (2.7 \times 10^{-6})\, e^{\left(7.8 \; \frac{R_{max}}{V}\right)} A_{max} \qquad \text{EQ 2}$$

The above expression assumes no interference from competing background radiation (i.e., dark nighttime conditions). Under daytime conditions the systems' illuminating energy density in the mapping volume must be significantly greater than solar radiation intensity integrated over the cameras shutter gate time. The ratio of laser to solar illuminating energy density (K) at maximum range and within the receivers optical bandwidth can be expressed as follows:

$$K = \frac{\frac{E_T}{A_{max}}}{I_s \; \lambda_f \; T} \qquad \text{EQ 3}$$

where Is is the sun's radiant intensity, λ_f is the bandwidth of the receivers spectral filter and T is the shutter open time. The latter is as follows:

$$T = \frac{1}{2} \left[(R_{max} - R_{min}) \; \frac{2}{c} \right] \qquad \text{EQ 4}$$

where the term in brackets represents the arrival time difference between laser energy reflected from the two extremes of the mapping volume. The factor 1/2 accounts for the 50% duty cycle of the binary coded shutter waveforms over the range acceptance window. Note that the energy ratio of EQ 3 includes no effects of atmospheric attenuation. It is assumed, as a first order approximation, that this attenuation will be roughly equivalent for both solar and laser illumination and is thus not a factor in the computation. Thus, from EQ 3 and 4, the required transmit energy for daytime operation is:

$$E_T = KI \qquad \text{EQ 5}$$

where R_D is the depth of the mapping volume (Rmax - Rmin). Assuming a worst case noon sun solar radiant intensity of 1400 watts per square meter per micron, a spectral filter bandwidth of .005 microns and a required energy ratio (K) of 20 db (for detection probabilities equivalent to that described previously), the required transmit energy for daylight operations is:

$$E_T = 2.3 \times 10^{-6} \, (R_D A_{max}) \qquad \text{EQ 6}$$

In summary, EQ 2 and 6 above define the required laser illuminating energy versus the size of the mapping region desired for night and worst case daylight conditions respectively. For reasonably large mapping volume depth (R_D), the transmit energy required for daytime operations is much greater than at night and, for relatively short ranges and all but onerous weather conditions, is not a function of weather. Thus, the mapping volume capability of the system ($R_D A_{max}$) from EQ 6 is daylight limited in accordance with available transmit energy as follows:

$$R_D A_{max} = 4.3 \times 10^5 \, E_T \qquad \text{EQ 7}$$

Equating EQ 2 and 6, the minimum visibility V for equivalent mapping capability at night is computed as follows:

$$V = \qquad \text{EQ 8}$$

where all dimensions are in meters.

The maximum readily available transmit energy in the visible spectrum with present technology can be provided by a frequency doubled NdYag laser. Such devices can provide 0.25 Joules of energy at 2-3 nanosecond pulse widths. With such a device, a LORDS system would be capable of providing 1/2 meter range resolution within a mapping volume ($R_D A_{max}$) as defined by EQ 7 of 100,000 cubic meters. Based on this and EQ 8, the Table I provides several examples of LORDS mapping volume capabilities for various system optical configurations. The configurations selected are restricted by the following practical optical considerations in providing the required angular field of view at an f number of 1.2.

a) lens diameter less than 10 cm

b) field of view less than 30 degrees

As a typical example taken from Table I, LORDS could provide an accurate 3D map of a spatial volume extending from 139 to 250 meters in range and of lateral dimensions at 250 meters of 30 meters by 30 meters (17 meters by 17 meters at the minimum range). This performance could be achieved in the worst case conditions of clear day noon sun or adverse weather with visibility restricted to 429 meters (approximately 1/4 mile).

Range resolution over the mapping volume is 1/2 meter (222 range cells) and nominal lateral resolution less than 1/10th of a meter. With 222 range cells required, a fully implemented LORDS system would require 8 cameras to gather this data from a single laser transmitted pulse. Alternately, a single camera system could be implemented, for which 8 laser transmissions would be required and all data gathered in 133 milliseconds.

TABLE 1

SAMPLE LORDS CAPABILITIES

A_{max} (HT x WIDTH)	R_{max}	R_D	R_{min} ($R_{max} - R_D$)	V_{min}
20 x 20	375	250	124	544
20 x 20	300	250	50	436
30 x 30	560	111	450	962
30 x 30	500	111	389	857
30 x 30	250	111	139	429
40 x 40	700	62	638	1377
40 x 40	350	62	288	688
40 x 40	175	62	113	344
50 x 50	900	40	860	1990
50 x 50	450	40	410	995
50 x 50	225	40	185	497
50 x 50	100	40	60	221

(NOTE: All dimensions in meters)

V. CONCLUSIONS

The LORDS system concept provides interesting potential as a means of rapidly gathering high resolution 3D data over useful mapping volumes. As such, it may find application in providing useful input for autonomous vehicle navigation, target analysis sytems, ground mapping systems and the like. As a result of its "snapshot" capability, the 3D data distortion associated with slower raster scan type sensors is eliminated. Since all data is captured from a single laser pulse transmission, the system has inherent advantages when covert operation is required. Unlike raster scan systems requiring sensitive oscillating mirrors to scan the beam over the mapping volume, LORDS has no moving parts and is thus inherently more rugged and reliable. LORDS is also eye safe when compared to raster systems which pose a safety hazard should scanning mechanisms fail and the transmit beam thus remain immobile in space.

Component limitations force the LORDS concept to be implemented in the visible region of the spectrum (i.e., below 1 micron). This, in turn, limits system range capabilities due to the effects of interferring solar radiation and severe weather. However, reasonable capability can be achieved in all but the most severe weather conditions. Given the system's inherent advantages, LORDS will find utility in those applications where distortion free, high resolution 3D is a necessary input for associated operations.

While this paper has dealt with LORDS capabilities when operating within the earth's atmosphere, LORDS also has potential for applications in space. Here, the effects of solar radiation are somewhat more severe, but atmospheric attenuation effects are eliminated.

The primary factor forcing operation into the visible spectrum lies in the present unavailability of large "gateable" CCD arrays of sufficient sensitivity in the near or far IR. Work in the development of such devices is being carried out under various programs. Success in such endeavors will permit LORDS operation in the IR, where both the effects of solar radiation and atmospheric attenuation are significantly reduced. The resultant range and mapping volume capabilities of the system would thereby be increased significantly.

NOTE: Robotic Vision Systems of Hauppauge, N.Y. holds a U.S. patent covering the LORDS concept.

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TECHNOLOGY TRANSFER: IMAGING TRACKER TO ROBOTIC CONTROLLER

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1. ABSTRACT

The transformation of an imaging tracker to a robotic controller will be described. MDAC has developed a multimode tracker for fire and forget missile systems. The tracker "locks on" to target images within an acquisition window using multiple image tracking algorithms to provide guidance commands to missile control systems. MDAC used this basic tracker technology with the addition of a ranging algorithm based on sizing a cooperative target to perform autonomous guidance and control of a platform for an advanced development project on automation and robotics. A ranging tracker is required to provide the positioning necessary for robotic control. This project was part of MDAC's Space Station B effort. A simple functional demonstration of the feasibility of this approach was performed and will be described. More realistic demonstrations are under way at NASA-JSC. In particular, this modified tracker, or robotic controller, will be used to autonomously guide the Man Maneuvering Unit (MMU) to targets such as disabled astronauts or tools as part of the EVA Retriever effort.

It will also be used to control the orbiter's Remote Manipulator System (RMS) in autonomous approach and positioning demonstrations. These efforts will also be discussed.

2. INTRODUCTION

McDonnell Douglas Astronautics Company (MDAC) has been developing imaging trackers for various Army battlefield applications for the past eight years. This technology uses two dimensional imagery from visible and infrared cameras with tracking algorithms for target acquisition, lock on, and guidance of a fire and forget missile or for autonomously pointing a laser designator. Field demonstrations of the current state-of-the-art have been very promising.

With MDAC's participation on the Phase B Space Station Program, a need for implementation of Automation and Robotics (A&R) on the Space Station was created by a Congressional Mandate for a technology thrust in A&R. Studies performed at MDAC indicated that a major area for immediate A&R application centered on the astronaut's extravehicular activity. The approach selected by MDAC focused on creating an astronaut's aide which would reduce the physical labor of material handling and boredom resulting from visual inspection and monitoring functions. The implementation of this approach would use as much of the existing NASA and other DoD capability as available. The existing hardware building blocks were (1) the existing Orbiter Cameras as the sensors, (2) the Remote Manipulator Arm System (RMS) on the Orbiter as the mechanical arm, (3) the Man Maneuvering Unit (MMU) as a platform, and the MDAC Imaging Tracker as the signal, data and control processor. The following sections of this paper describe the joint effort between MDAC and NASA-JSC in transforming the Imaging Tracker into a Robotic Controller for a variety of A&R space applications using these building blocks.

MDAC-HB has been developing tracking systems for anti-armor weapons since the early 1980s. The first system was for Tankbreaker, a fire-and-forget missile. This system required high performance tracking in a highly cluttered hostile environment with countermeasures while occupying the small volume allocated by the missile. Missile guidance functions were also performed by the tracking system.

Since packaged volume and system performance were critical to the system, a programmable based tracker design was chosen. However, image processing tracking algorithms are calculation intensive, requiring a special purpose signal processor dedicated to the function. System architecture and proper partitioning and allocation of the functions to the hardware was critical to prevent a computation bottleneck limiting the required performance. Figure 1 shows the architecture of the multimode tracker.

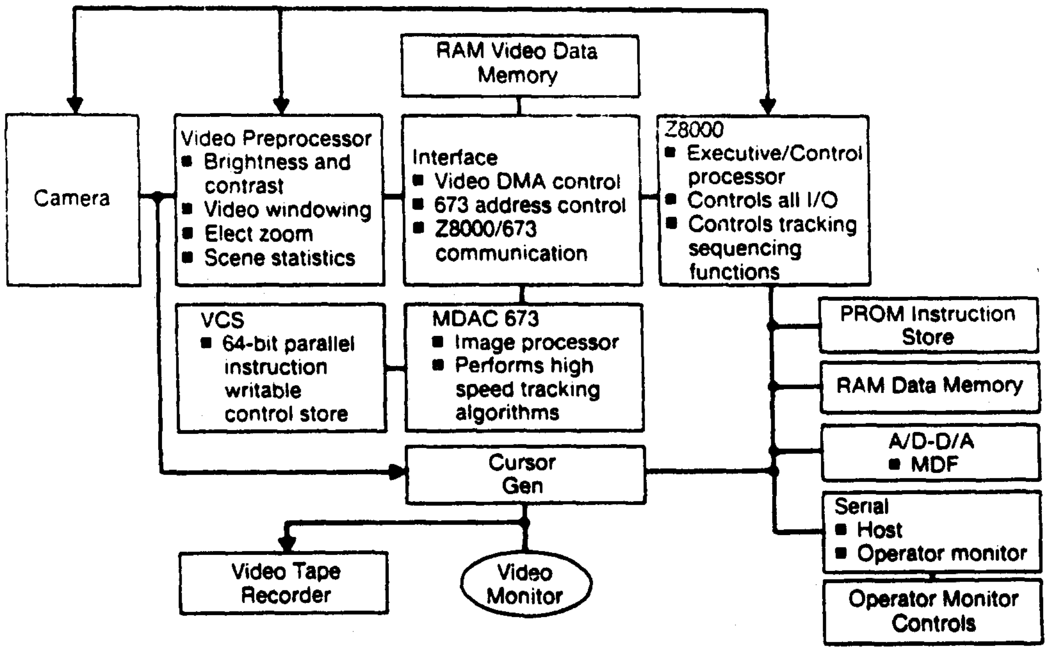

Figure 1. MDAC 673 Tracker Configuration

The tracker is partitioned into three functional elements: video preprocessor, an image tracking processor, and an executive/control processor. These partitioning boundaries optimize the performance by allocating specific tasks to stages to maximize the throughput of the system.

The video preprocessor conditions the video image signal to match the throughput of the next stage, image tracking processor. To match the video data with the bandwidth of the image track processor, data compression is performed by either excluding regions that are of no interest or by pixel averaging. This stage enhances and bandwidth limits the video signal to match the requirements of the image tracking processor. Four functions are performed: video gain and bias compensation, processor windowing, histogramming and reformatting the image for track processing.

The image processor MDAC 673 is a high speed, 10 MOPs, special purpose 64 bit microprogrammable signal processor. All high speed image tracking functions are performed by the 673. Six concurrent tracking algorithms are performed in the multimode tracker, 1) centroid, 2) correlation, 3) conformal gate, 4) guard gate, 5) coast mode, 6) moving target indicator. Ranging to the target is also computed based on image size. The primary trackers are centroid, correlation and conformal gate. Centroid is a contrast tracker that finds the center of the target exhibiting intensities above or below a controllable threshold. Automatic gate sizing boundaries are recomputed and adjusted each frame. Correlation is a feature tracker that tracks by finding the best match of a video reference of a previous frame and the scene. Conformal gate is a statistical tracker that classifies as either background, target, or unknown. This tracker finds the target boundary and maintains the tracker gate size to enclose the entire target. Each of these trackers exhibit different strengths and weaknesses. Under the direction of the executive/control processor, these differences are exploited.

The executive/control processor directs the operation of the trackers. When it detects that one of the trackers is going astray, either by loss of track quality or aimpoint, it reinitializes the tracker, thus maintaining a strong lock. The executive/control processor also performs all I/O for the tracking system. This multimode tracker was designed to provide the capability of missile guidance as well as track functions. Therefore the executive/control processor not only directs the executive functions of the multimode tracker but also uses these results in computing the guidance commands and pointing the image sensors. All I/O functions are provided by this stage, thus relieving the image track processor from a heavy burden and allowing the high speed computations required. Operator control is provided by both a hand controller and CRT terminal link.

4. ROBOTIC CONTROLLER DEVELOPMENT

A Congressional Mandate sought to provide an A&R technology insertion thrust into NASA's programs such as the Space Station. However, the budget was limited and time for incorporation on the Space Station very short. MDAC had identified areas of focus for A&R with robotic assistance to EVA activities being high on the list. Joint planning meetings between MDAC and NASA-JSC resulted in the guidelines of using existing technology in a functional feasibility demonstration of tracking, guidance, and control as the most appropriate for showing the near term capability of supervised autonomous (Telerobotic) control of mechanisms such as the Orbiter RMS arm and platforms such as the MMU. MDAC Imaging Tracker could certainly guide an object such as a mechanical arm or platform to a target but the tracker would require range information for it to do positioning. Therefore, an algorithm to estimate range based on target size was incorporated with the basic tracker algorithms. The MDAc Imaging Tracker being primarily a software driven system was well suited for being reprogrammed to incorporate ranging with the tracker guidance to perform relative positioning.

Fucntional demonstrations of relative guidance and positioning using a wheeled platform being guided by the MDAC Imaging Tracker were developed by MDAC and JSC. This Advanced Development Project was proposed as an add on the MDAC Phase B Space Station Proposal in March of 1985 and the demonstrations performed in July.

5. EVA RETRIEVER AND MDF EFFORT

A joint effort by four divisions at NASA-JSC was undertaken in 1987 to develop the technology and demonstrate an EVA retriever for astronaut rescue in the event that he becomes separated from the shuttle or space station. Under a contract with the NASA-JSC Tracking and Communications Division, the MDAC multimode tracker was mounted on a free wheeling robotic platform and modified to perform autonomously the telerobotic functions of search, discriminate, designate, acquire, and guide the robotic platform to a specified target. All functions are passively performed by processing the video image. The tracking robotic controller under supervisory control of an operator automatically searches a field of regard for a previously selected object. Once an object appears in the camera's field of view, the multimode tracker scans the object to determine if it is the selected one. If not, it continues to search until the selected object is found. Once found, the tracking robotic controller initializes the robotic platform by aligning the camera's boresight with the platform wheels, calculates guidance commands and controls the platform motion towards the object. Range is determined from image size. Once the robotic platform reaches an engagement range the robotic tracking controller tops the motion and is ready to command target grappling. Demonstrations of these functions were performed in July 1987.

The tracker also is used to provide automatic acquisition and tracking functions to an EVA Retriever developed system operating on an airbearing table in Building 9 at NASA-JSC. This EVA Retriever consists of a modified MMU, a television camera, a 3-D laser ranger, a voice recognition and synthesis system, two robotic arms with grappling mechanisms, and a guidance and control computer. The MDAC multimode tracker provides automatic acquisition and tracking functions to the guidance and control computer. The EVA Retriever program is a 3 phase program with each phase lasting one year. Performance of the system improves each year until a complete autonomous retrieval is demonstrated on the airbearing table and the system technology is ready for a shuttle demonstration.

Autonomous guidance and control of robotic arms will be required for servicing space satellites. The MDAC robotic tracking controller is also being integrated with the Manipulator Development Facility (MDF) arm at the Johnson Space Center to demonstrate supervised telerobotic capacity to approach, position, engage, and retrieve (or assemble) payloads under supervised but autonomous robotic control. The MDF arm was chosen for this demonstration because it represents the implementation of teleoperation in space and can readily be used for the telerobotic demonstration. The existing MDF shuttle software is used to control the arm's movements. A small modification to the terminal interface of the MDF was made to allow communication with the MDAC tracking robotic controller.

The tracker will process television camera signals to determine target position, orientation and attitude to guide the MDF arm to the satellite target. Communication interface to the MDF system will be made through an RS232 link to the SEL 32/77 computer. The robotic tracker will monitor arm position and control movement by issuing X, Y, Z, pitch, yaw, and roll commands as calculated dynamically from target images. Initially, an operator will intercept and approve each arm motion command. After successful integration, the demonstration will be repeated under fully autonomous telerobotic control.

6. SPACE STATION AREA SURVEILLANCE

The current Space Station baseline configuration includes a number of television cameras to be used for area surveillance, including the monitoring of EVA operations. These cameras are to be installed at various locations on the external structure, as well as inside the pressurized zones. Images will be displayed to the crew and/or transmitted to the ground.

Camera control includes pointing direction, zoom, focus and aperture. The current baseline allows the camera control to be exercised from either an on board work station or the ground. Since EVA operations will occur frequently and can last several hours, a significant amount of IVA crew time will be required just to keep the EVA objects within the camera's field of view. Manually controlled camera pointing becomes an especially demanding task when the zoom facility is invoked to provide closeup viewing operations.

Supervised autonomous camera control for observation of EVA or other moving objects, without the full attention of an IVA crew member, would significantly improve crew productivity. The IVA crew could handle other work station tasks while monitoring EVA activity on dedicated or shared monitors. The MDAC robotic tracking controller tests are specifically designed to prepare for these autonomous functions.

7. CMOS TRACKERS

A design of an advanced CMOS multimode tracker is currently being developed. This packaged version scheduled to be completed in 1988 is an advanced solution to the high performance tracking problem. The implemented design combines proven tracking techniques with the latest VLSI components to meet the requirements of acquiring and tracking images in large fields of regard.

8. SUMMARY AND CONCLUSIONS

This joint MDAC and NASA-JSC development demonstrates the advantages of technology transfer. There were major savings made in development costs, schedule, and risk. The key factors were the open communications that flowed between MDAC and JSC, the support that the program offices at MDAC and JSC provided, and the breadth of technology insight the participants had. Most certainly there will be better ways to do these functions; however, rather than starting from scratch, the focus was on performing these key functional demonstrations with existing, packaged, hardware to win the acceptance of the concept by the operational and management staffs so the technology would be inserted or provided for in the baseline program.

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Stabilized Image System for Mobile Robots

21 April 1988

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ABSTRACT

Innovations in tube camera technology allow for electronic stabilization of the video output image. This technology offers a low-cost means to provide a stabilized image from a moving teleoperated vehicle for steering, isolation of the gunner's targeting image from weapon recoil, and other disturbances. This may make possible both target detection and identification while the vehicle is in motion. It will also provide for additional flexibility in a robotic vehicle vision system by allowing scanning without mechanical turret motion and providing capability to zoom without changing the camera lenses.

An experimental system has been constructed, and a preliminary demonstration of the concept has been evaluated. This paper will present the results of this initial experimental system and then focus on future research activities. It is important to provide demonstrations of this technology in realistic environments and conditions. This approach is seen as a key towards acceptance of electronic stabilization technology.

1.0 INTRODUCTION

Recent developments with tube-type video cameras have provided a mechanism for electronic image stabilization for mobile robotic vision sensors. This technology offers a number of advantages over current designs. The need for a stabilized gimbal platform can be eliminated for systems in which the seeker is isolated from disturbances. Electronic image stabilization techniques can substantially reduce system cost, weight, and power requirements. In addition, electronic gimbaling can provide near instantaneous slew capability to enhance tracking performance and seeker isolation characteristics.

1.1 ELECTRONIC IMAGE STABILIZATION CONCEPT

The concept of image stabilization can be easily understood by examining the operation of video tube cameras. A simplified drawing of a typical vidicon tube is shown in **Figure 1**. The camera lenses project the observed image onto the glass faceplate, behind which is a photoconductive material. An electron beam is aimed at the photoconductive surface. The beam current is directly proportional to the amount of light reaching the beam spot. A set of magnetic coils focuses and deflects the electron beam in a standard raster scan pattern.

Electronic gimbaling is possible when the raster scan pattern is reduced in size (underscanned). The number of lines and sweep pattern are left unchanged; only the magnitude of the deflection coil currents is reduced. Thus the photoconductive surface area that is scanned is diminished. Adding a dc level to the horizontal deflection coil current shifts the entire scan pattern either left or right on the vidicon faceplate. To an observer watching the TV screen, the camera appears to pan as the dc deflection coil level is changed. The amount of panning freedom (electronic gimbaling capability) depends on the amount of underscanning and the camera optical field of view. This motion of the entire scan pattern simulates the effect of a pitch/yaw gimbal set (see **Figure 2**).

Controlling the raster scan size allows for an electronic zoom feature for vidicon cameras. The smaller the size of the pattern, the greater the zoom. A diagram for the camera control system is shown in **Figure 3**. This zoom can continue until the resolution of the camera is reached. After this point, enlargement of the image is accompanied by increased blurring.

Rolling the scan pattern is also possible by mixing vertical and horizontal scan signals. Multiplying the two scan signals by sine and cosine of the desired roll angle, as shown in the camera control system diagram, produces a tilted scan pattern. A four-quadrant multiplier chip allows a full 360° roll control of the raster scan pattern. Sine and cosine terms are produced digitially in the camera controller processor.

A stable video image is achieved by measuring camera motion and commanding a pitch, yaw, or roll deflection angle to compensate for that motion. Camera motion is measured by using gyro angular information or integrating inertial rate sensors. Since a scan pattern is generated every 1/60-second, the camera control commands can change at this rate.

1.2 HISTORICAL BACKGROUND

This electronic stabilization of a TV seeker image was originally developed in the Electro-Optical Simulation Systems branch at MICOM by a Government engineer, Bill Phillips, and has resulted in MICOM invention disclosure AMP 4331. The concept has also been successfully demonstrated on the Precision Deep Attack Missile System (PDAMS) test vehicle. In the PDAMS program, a modified commercial TV camera was used as the missile's seeker. The missile rate sensors provided signals for image stabilization and autopilot pitch loop damping.

As a strapdown seeker, the tracker signal provided a guidance command as well as rate term for the electronic gimbal. A block diagram showing a single axis of a tracker loop for a traditional gimbaled platform seeker is shown in **Figure 4** to contrast with the approach using the electronically stabilized camera tracker loop (see **Figure 5**). The camera image is stabilized by commanding electronic gimbal angles that compensate for missile body motion. The tracker error signal is multiplied by a gain term and processed by a compensation network to provide frequency shaping. This processed signal is used as an estimate of the target line-of-sight rate for missile guidance. The desired seeker electronic gimbal rate to continue tracking the target is the line-of-sight rate minus the missile body rate. The desired seeker gimbal rate is integrated to produce an electronic deflection coil command.

The PDAMS design was successfully simulated in a six degree-of-freedom simulation. As the proportional guidance algorithm was being formulated, hardware-in-the-loop testing added a high degree of confidence in the weapon's terminal performance. The program culminated in actual field testing that showed acceptable terminal accuracy. Rexham Aerospace and Defense Group (RADG) has played a key role in the PDAMS program and the development of image stabilization technology.

2.0 BREADBOARD ELECTRONIC IMAGE STABILIZATION EXPERIMENTS

Applying this electronic stabilization technique to robotic vehicles was a natural extension of current RADG activities. Several current mobile teleoperated vehicles have difficulties with induced image jitter while in motion. The sensors are typically mounted on a turret assembly along with weapons. It is difficult to design a turret control system that has both the high bandwidth to provide a significant degree of isolation from road disturbances and the stiffness to hold counter weapon recoil forces. Such a turret would likely be too massive to allow for the rapid angular control necessary to compensate for rough terrain at moderate speeds. An in-house project consisting of a breadboard system was set up to demonstrate the feasibility of electronic image stabilization for mobile vehicles.

This effort used PDAMS camera and rate sensors to measure inertial motion. The rate sensor package was physically mounted on the same platform as the camera to ensure that measured signals were identical to those that the camera experienced. An IBM PC clone controlled camera deflection coil dc levels providing for electronic gimbaling. A Metrobyte data acquisition board was used to allow the input and output of analog signals to the computer. An analog filter to reduce rate sensor noise was also included in this configuration. A block diagram of the experimental setup is shown in Figure 6.

The camera control software included a bias estimation filter, a numerical integrator to produce an angular measurement, and an output washout filter for vehicle turns and gradient changes. The washout filter smoothly moves the camera image back to the center of the screen; thus, high frequency motion jitter and other disturbances were successfully removed from the output image. A block diagram of the camera control software for this breadboard test is shown in **Figure 7**.

For the demonstration, a second camera was mounted on the turret next to the image stabilization camera and the gyro package. The outputs from these two cameras were connected to a split-screen device where the output of each could be viewed simultaneously. This provided a dramatic comparison between the stabilized and unstabilized cameras. The output of both cameras was recorded on videotape for a wide variety of motions. To further demonstrate the system, the entire experimental setup was placed in the back of a pickup truck. The video from the two cameras was recorded while the vehicle moved at slow speeds over rough terrain.

The experimental setup performed adequately, showing a marked reduction in image motion for the stabilized camera. There was some blur associated with the stabilized image when compensating for high-frequency motion, and the cause of the blur is under investigation. Using rate sensors in this breadboard system had several drawbacks, with gyro biases chief among them. A tilt sensor model is expected to ease design problems in the following phases. The conclusion drawn from this program is that electronic image stabilization is possible and could provide significant improvement in the image quality for a moving teleoperated vehicle.

3.0 FUTURE RESEARCH ACTIVITIES

The future in-house research activities for electronic image stabilization technology include the following projects: improvements to reduce blur while compensating for high-speed motion, elimination of gyro bias, adaptation of the circuit concept to color cameras, and enhancement of system interface. Concepts to eliminate inertial sensors and other costly components will be pursued. The product of this research effort will be a working brassboard robotic vision system that is portable and is flexible enough to interface with standard mobile robot sensor suites.

The PDAMS camera allows only for discrete zoom points. Continuous electronic zoom is possible and is part of our phase II design. The roll control concept has been investigated by other researchers. Their approach, using vertical and horizontal deflection coils of the same inductance, has resulted in a power-hungry design. Our roll concept will use low power resonate raster scan circuitry but will contain dual coils for each axis.

The electronic image stabilization concept can be applied to other tube cameras, such as Newvicon and Ultracon, to allow performance under low-light situations. Adaptation to color cameras is under investigation. A one-inch vidicon tube will allow for resolution of 1200 to 1000 lines; for wide gimbaling applications, this must be increased. Various techniques to improve camera resolution are being pursued for future systems.

In addition to camera development activities, alternative stabilization concepts are being formulated. Among the current promising concepts are (1) using the phase component of the image FFT to provide the image stabilization signal and (2) high bandwidth image tracking. Both of these ideas may eliminate inertial sensors in the system design, expand the electronic image stabilization concept, and broaden the potential applications.

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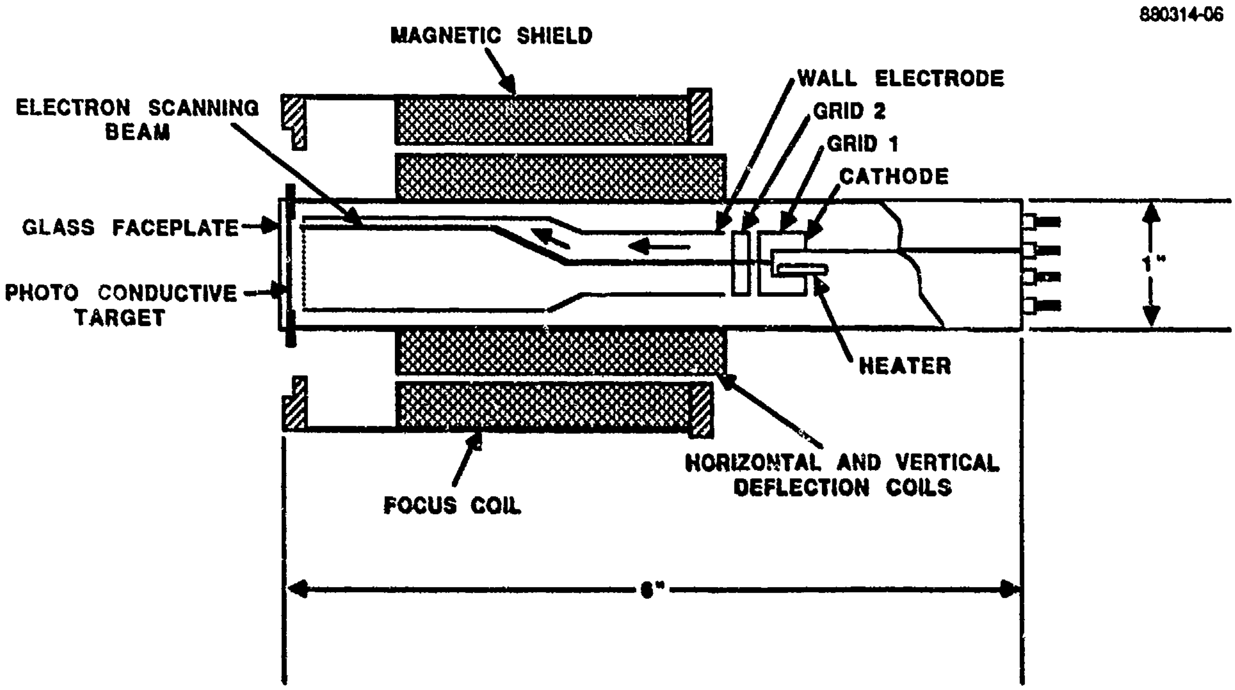

Figure 1. Electronically Stabilized Camera

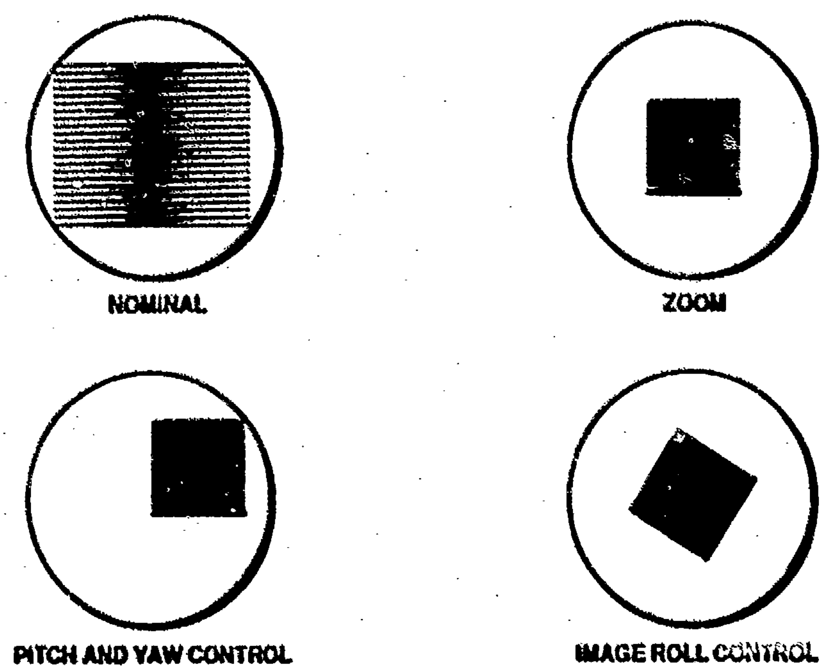

Figure 2. Raster Scan Pattern Changes

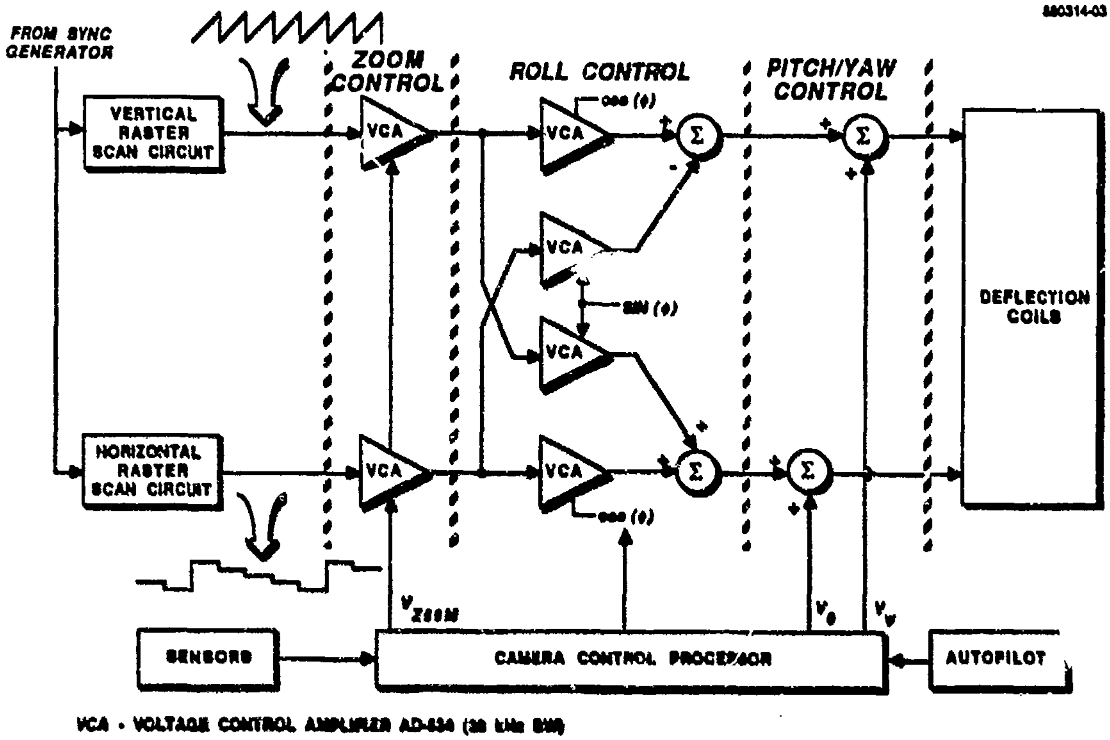

Figure 3. Camera Control System Block Diagram

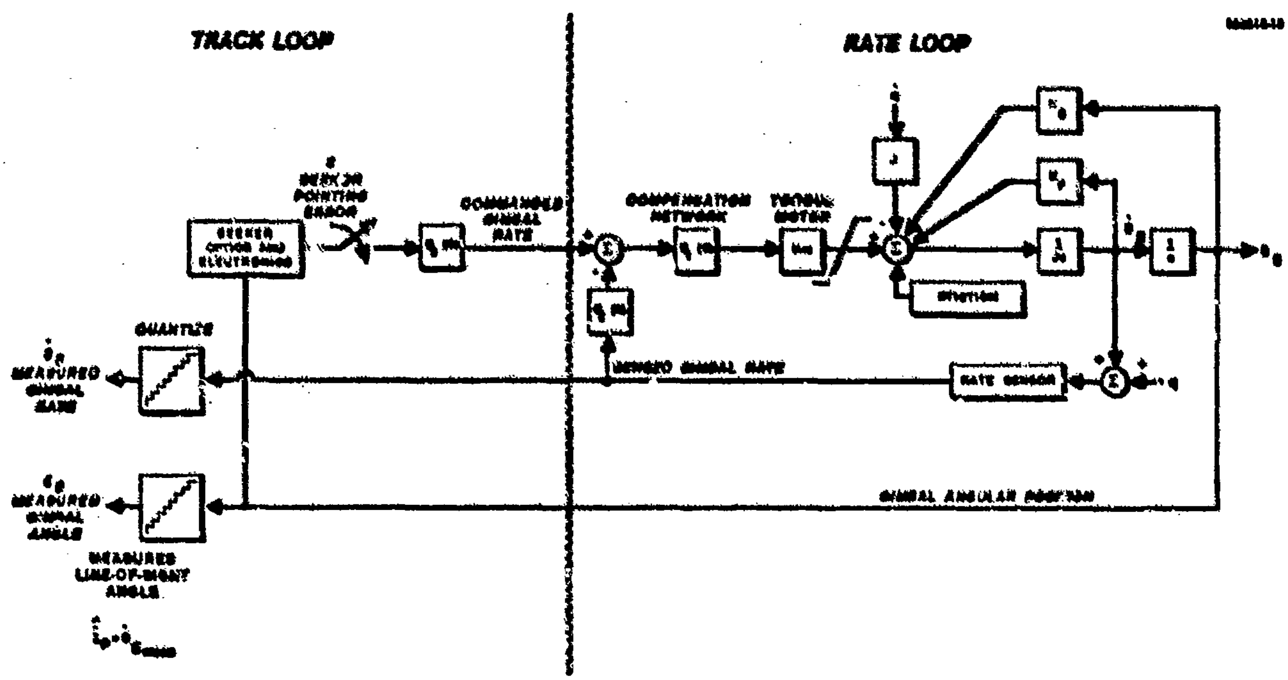

Figure 4. Block Diagram of Seeker Servo Control Loops

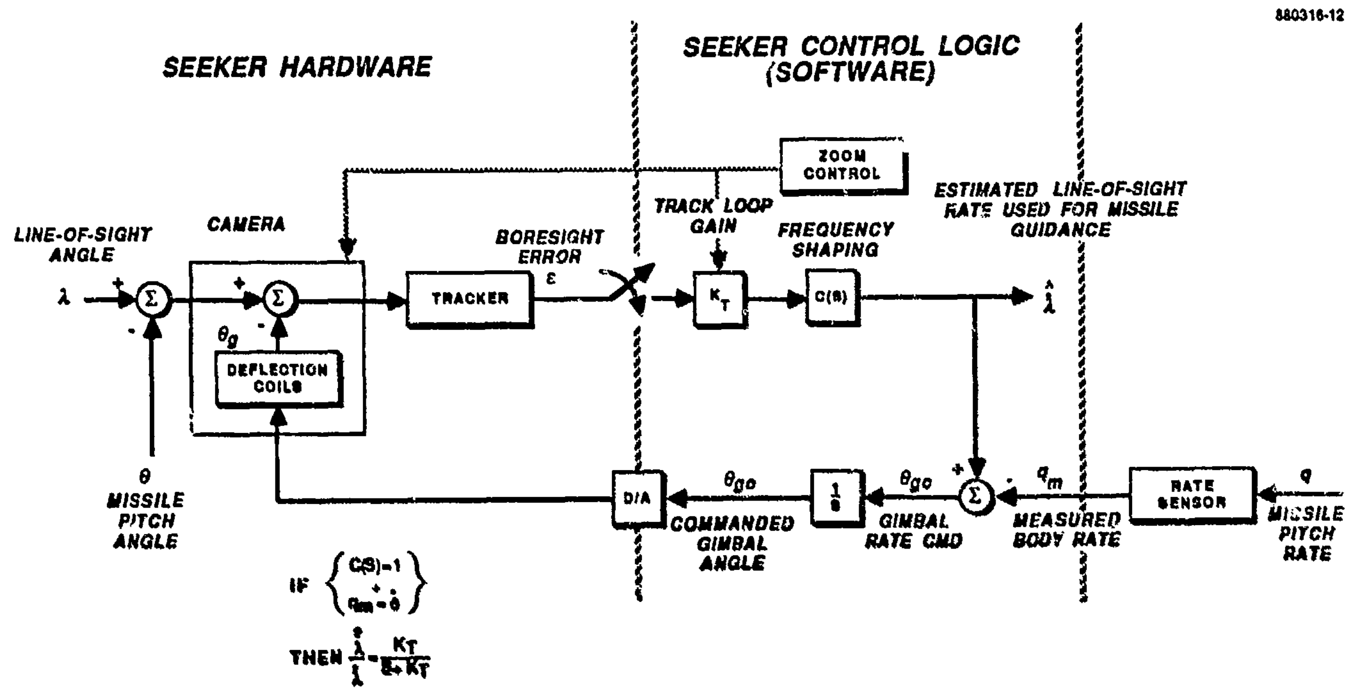

Figure 5. Stabilized Camera Seeker Concept

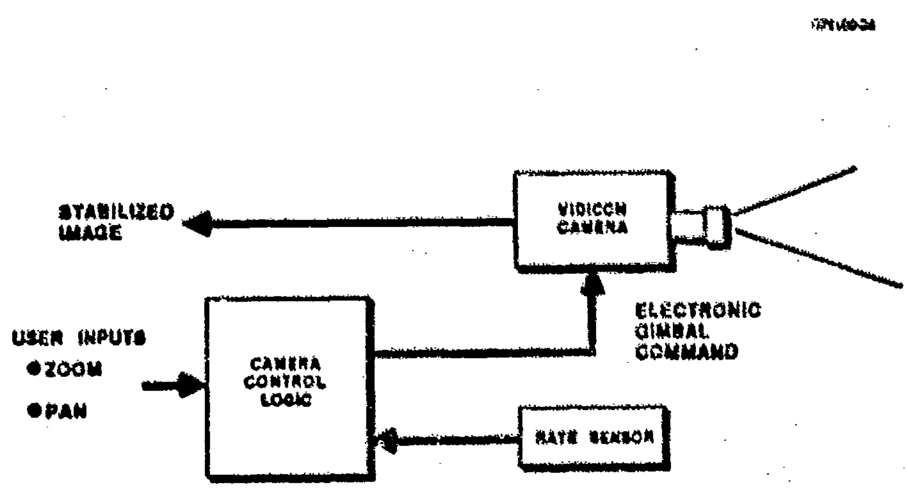

Figure 6. Robotic Vehicle Electronic Image Stabilization

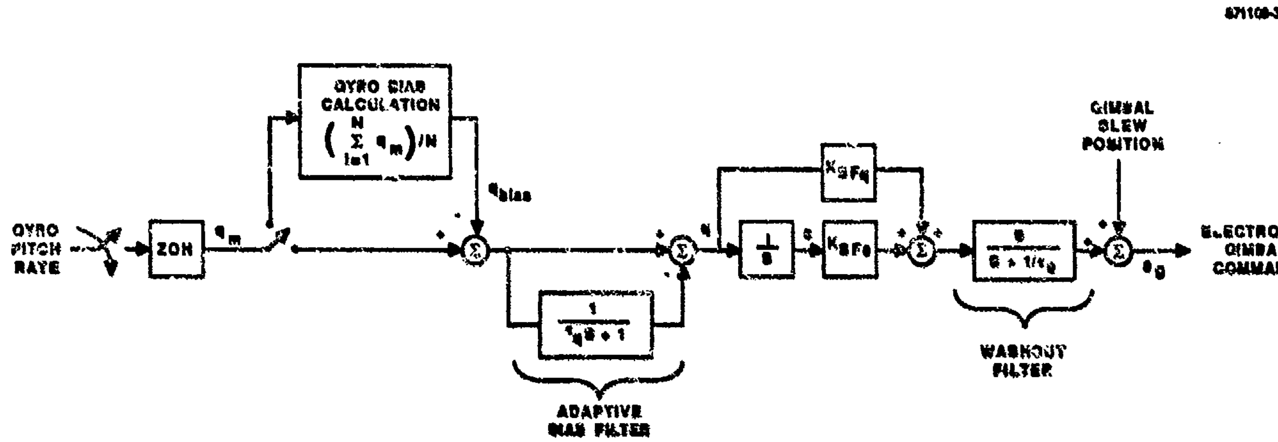

Figure 7. Camera Control Software

Two Dimensional Convolute Integer Technology for Digital Image Processing

Thomas R. Edwards
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An Incubator Company
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A demonstration of results from the application of Two Dimensional Convolute Integer Operators will be presented. The results for classical replacement point convolutions and magnification by interstitial point generation will be displayed on a PC micro-computer with a high resolution large screen (25 in) color graphics monitor.

The sensitive two dimensional frequency response of Two Dimensional Convolute Integer Operators will be seen on a number of test images, ranging from a noisy German Panzer tank image to Landsat data. Images of a noise free tank without loss of detail, images of noise bands removed, families of edge contours from low frequency (fat edges) to high frequency (thin line boundaries), Laplacians, curls, magnification and feature extraction will be presented.

Two Dimensional Convolute Integer Technology represents a family of innovative image processing operators for high-speed, two dimensional frequency-sensitive, theoretically correct classical convolutions, interstitial point generation, and missing or bad value replacement. Two Dimensional Convolute Integers Operators are mathematically equivalent to partial derivatives, a correct approach towards curl, divergence, Laplacian and gradient magnitudes and directions, and high resolution magnification.

This VAX-based PC-linked, high resolution, color image display convolution software will be described along with TREC's Digital Image Processing Environment in the Research Institute of the Johnson Research Center at the University of Alabama in Huntsville.

TREC, Inc is the first incubator company on the campus of the University of Alabama in Huntsville, associated with the Center for Applied Optics and the Center for Robotics and Artificial Intelligence.

Mr. Edwards obtained his graduate education in Physics from the State University of New York at Buffalo and came to the Marshall Space Flight Center/Space Sciences Laboratory via the National Academy of Sciences Post Doctoral Program. In 1984 he joined TREC, Inc to pursue the development of Two Dimensional Convolute Integer Technology.

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Session IV Program A

Robotic Systems

Chair: Chuck Shoemaker, Human Engineering Laboratory

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arguments [7]. This results in sums over nonzero basis functions in the piece for evaluation for a given argument. Although this approach is less intuitive, it is inherently more stable computationally thereby providing better accuracy and requires less storage for coefficients [8, 9]. Currently, B-splines are defined only as a function of one variable and as a result, multidimensional modeling using B-splines is restricted to the tensor-product of one-dimensional spaces of polynomial splines.

In attempting to model six degree of freedom robots, one is faced with the problem of B-spline modeling of functions of as many as six variables consisting of three position and three orientation coordinates. The tensor-product restriction requires the set of data points to consist of all combinations of partitions of each of the independent variables. Algorithms were developed for functions of six variables which are straightforward generalizations of the work of de Boor [10] for implementing B-spline modeling in one and two dimensions. In what follows, we descibe the results of applying these algorithms to modeling computer-generated data for the Stanford manipulator, a six degree of freedom robot with known solutions.

RESULTS

The hyper-surface modeling algorithm was implemented and tested using computer generated data for the Stanford manipulator, a six degree of freedom robot with 5 revolute joints and one prismatic joint. All programs were written in Fortran and run on a Vaxstation 2000 workstation.

The data required for model derivation was calculated using the forward and inverse kinematic equations reported by Paul [11]. The distance d_2, between the coordinate frame fixed in link 1 and the frame fixed in link 2 was assumed to be 200mm.

The results are presented in terms of the position, approach and orientation vectors because they are easy to interpret geometrically. The position vector describes the location of the end effector. The approach vector describes the direction from which the hand would approach an object. The orientation vector describes the orientation of the hand from one side of the gripper to the other. Specification of the end effector state using this nomenclature requires nine parameters while the space is only six dimensional. To insure an independent set of state variables the end effector position was described by cartesian coordinates and its orientation by Euler angles [11].

The models were derived using data which spanned a hyper-box subspace of the working envelope. The first three dimensions of the box define a rectangular solid in the reference coordinate frame and the last three define the range of the Euler angles. The location and size of the box are given in Table I. The ranges of the six joints corresponding to this hyper-box in the reference coordinate frame are given in Table II.

Table I. Dimensions of modeled region of the hyper-space.

Parameter	Minimum Value	Maximum Value	Units
x	-0.60	-0.20	meters
y	0.25	0.65	meters
z	0.00	0.40	meters
θ	33.75	56.25	degrees
ϕ	33.75	56.25	degrees
ψ	33.75	56.25	degrees

Various models of this region of the work space were developed and tested. The error analysis included both the errors in the joint models and their partial derivatives and the error at the end effector resulting from the modeled joint values. The joint errors were calculated as the absolute value of the difference between the modeled joint value and the calculated value from the analytic solutions. The errors in the partial derivatives of the joint models for the first three joints were evaluated by comparison with the partial derivatives of the analytic joint equations. Partial derivatives for the models of the last three joints have not yet been evaluated.

Table II. Joint Ranges required to access the modeled hyper-space.

Joint Variable	Minimum Value	Maximum Value	Units
θ_1	-55	-4	degrees
θ_2	-90	-32	degrees
d_3	250	950	mm
θ_4	20	67	degrees
θ_5	52	131	degrees
θ_6	56	165	degrees

The end effector errors were calculated as the difference between a commanded end effector position and the position computed by evaluating the analytic forward equations at the modeled joint values. Errors in position are presented as the magnitude of the error vector. Errors in the orientation and approach vectors are presented as the angle between the commanded vector and the vectors resulting from the modeled joint values. This angle is computed from the magnitude of the cross product of the acheived and desired vectors.

The end effector errors were computed over a trajectory in the modeled hyper-space. The desired trajectory was specified as a diagonal line between opposite corners of the box defined earlier in this paper. The position components of the trajectory were increasing while the orientation components were decreasing. The joint models were evaluated for 51 equally spaced points on this trajectory.

Joint Errors

B-spline models of the joints were quite accurate when evaluated for points not included in the model derivation. The rms, mean, and maximum errors in the six joints of the Stanford manipulator are presented in Table III. These errors were computed by evaluating the models over the entire hyper-space at points equally spaced within the intervals between the knots. All joints were modeled using 6 points per axis. The first five joints were evaluated at 3 points per interval per axis. The last joint was evaluated at 1 point per interval per axis. None of the joints were evaluated at the knots because the error is theoretically zero there.

Table III. Error in Fourth Order B-Spline Joint Models

Joint Number	RMS Error	Maximum Error	Mean Error	Units
1	.248E-02	.980E-02	.163F-C2	degrees
2	.411E-02	.492E-01	.207E-02	degrees
3	.147F-01	.114E+00	.868E-02	mm
4	.442E-02	.768E-01	.220E-02	degrees
5	.616E-02	.867E-01	.260E-02	degrees
6	.467E-02	.479F-01	.241E-02	degrees

Errors in Joint Partial Derivatives

The partial derivatives of the joint models with respect to x, y, and z are denoted by f_x, f_y, and f_z respectively. The errors in the partial derivatives of the joint models reported in Table IV were evaluated at the same points used in the joint error analysis excluding those in the outside subintervals, where the lack of gradient information at the boundaries of the modeled region compromise the performance of the models for gradient purposes.

Table IV. Errors in Partial Derivatives of the Joint Models

Joint Number	Differential	Rms Error	Maximum Error	Mean Error	Units
	f_x	.172E-04	.795E-04	.101E-04	degrees/mm
1	f_y	.257E-04	.688E-04	.181E-04	degrees/mm
	f_z	.450E-07	.133E-06	.370E-07	degrees/mm
	f_x	.234E-04	.104E-03	.134E-04	degrees/mm
2	f_y	.212E-04	.942E-04	.130E-04	degrees/mm
	f_z	.214E-04	.129E-03	.148E-04	degrees/mm
	f_x	.854E-04	.403E-03	.577E-04	mm/mm
3	f_y	.107E-03	.443E-03	.740E-04	mm/mm
	f_z	.873E-04	.336E-03	.568E-04	mm/mm

Errors at the End Effector

The graph in Figure 1 shows the magnitude of the vector between the desired end effector position and the position calculated using joint vlaues from fourth and sixth order models. All models were derived using six data points per axis. The minimum error occurs at the knots, and increases as the distance from the knots increases. The maximum error in each lobe of the graph occurs approximately midway between the knots. The first and last lobes correspond to the ends of the calibrated area; the error in these regions is significantly greater than in other regions of the trajectory.

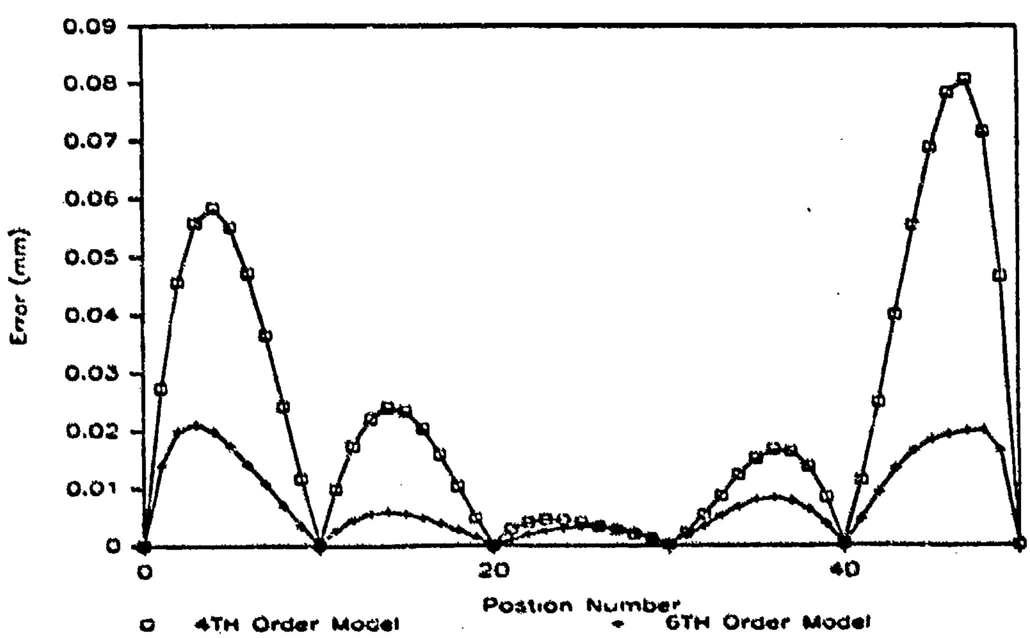

Figure 1. The effects of model order on end effector position error.

The errors in the angles of the orientation and approach vectors over the trajectory are shown in Figure 2. As is expected the error is greater near the ends of the trajectory, where the joint errors were greatest.

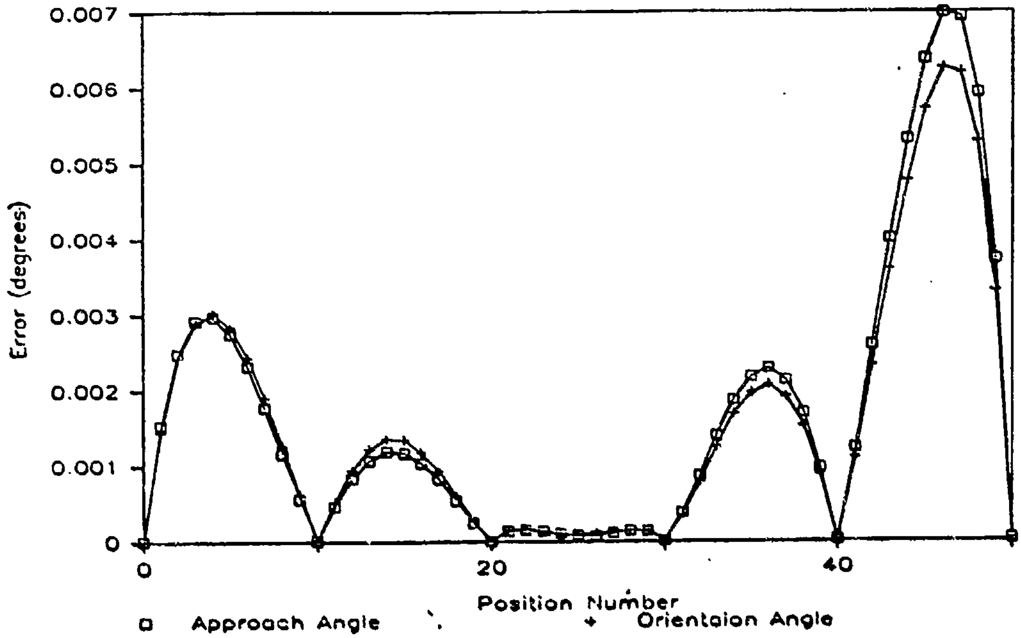

Figure 2. Errors in the angles of the orientation and approach vectors resulting from fourth order joint models.

Parameters which Affect Model Accuracy

Model accuracy was affected by the position and number of knots, the order of the spline, and the location of the modeled hyper-box. Table V presents the errors in joint 1 for different order models representing the modeled region of Table II translated in the hyper-space. Model performance clearly improves with increasing order, a fact further substantiated by the overall effect of model order on end effector error as shown in Figure 1. Comparison of the fourth order result from Table V with the analagous joint 1 result from Table III demonstrates the potentially profound impact of the location of the modeled hyper-box on model accuracy.

Table V. The Errors in Various Order Models of Joint 1.

Model Order	RMS Error	Maximum Error	Mean Error
2	.193E+00	.105E+01	.117E+00
3	.687E-01	.385E+00	.294E-01
4	.362E-01	.239E+00	.134E-01
5	.229E-01	.173E+00	.714E-02
6	.196E-01	.147E+00	.735E-02

The number of data points used to generate the models also has a significant impact on their accuracy. The error in the end effector position resulting from fourth order joint models derived using six and eight data points per axis is shown in Figure 3. Comparison of Figures 1 and 3 reveals that the fourth order model derived using eight points per axis performs nearly as well as a sixth order model derived using only 6 points per axis.

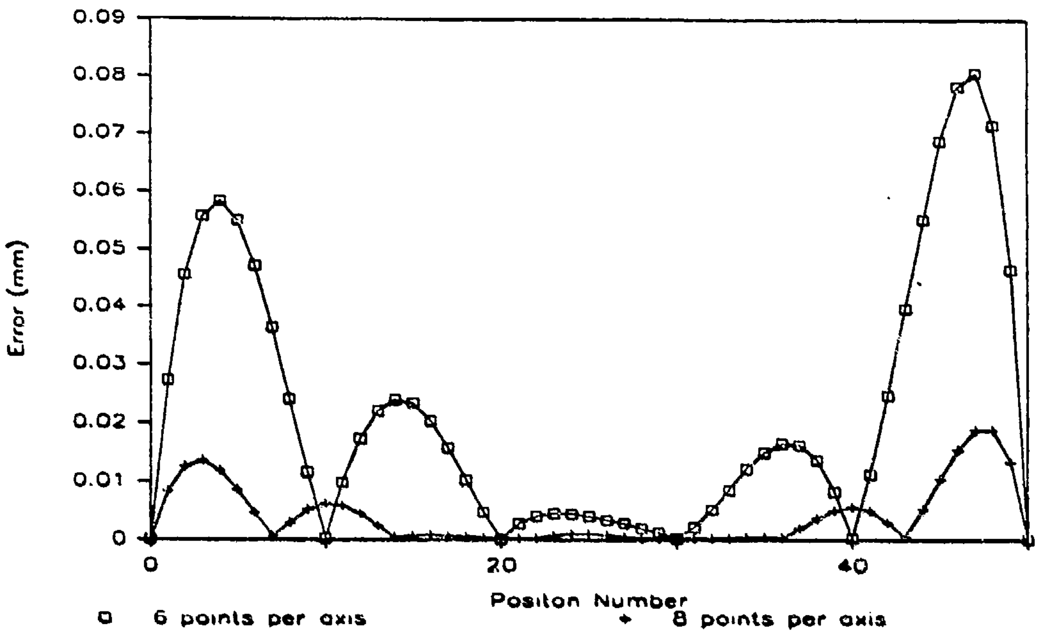

Figure 3. The effects of the number of data points used in model derivation on end effector position error.

CONCLUSIONS

The hyper-surface modeling technique results in extremely accurate robot joint models which, when differentiated, accurately represent the true partial derivatives of the joints. The error in the end effector location, computed using the analytic forward equations, resulting from the error in the joint models is also very small.

The technique presented herein may be used for robots of any configuration. It enables closed form solution of non-wrist partitioned robots which previously required iterative solution.

The models are of sufficient accuracy to indicate that they may result in more accurate solutions than analytic solutions when the robots differ significantly from the ideal. Common deviations from the ideal include manufacturing errors and failure of the robot to obey rigid body assumptions. These deviations are extremely difficult to model analytically but may be handled very simply using this modeling technique. If measured data as opposed to calculated data are used to derive the models, the compensation for manufacturing errors is automatically built into the models.

Compensation for flexion of the linkage under load is also very straightforward. The payload is simply included as another independent variable in the models. That is, the data used for model derivation includes various payloads as well as the joint and end effector data described earlier. Except that the model becomes n + 1 dimensional no other compensation is necessary.

The relationships identified between model accuracy and model order, the amount of data used, and the location of the modeled space may be used to design robot joint models according to various design criteria. They may be designed for different accuracies in various regions of the work envelope or for moderate accuracy in end effector orientation but extreme accuracy in position. If speed is important the number of on-line calculations can be minimized without jeopardizing accuracy by using lower order models derived from a more dense data set or converting to the standard piecewise polynomial basis.

The multi-dimensional modeling algorithm is appropriate for robots for both space and commercial applications. Commercial applications include robots which require extreme accuracy, very large or flexible robots, and "loose" robots which require accuracy enhancement to compensate for mechanically induced error.

The modeling algorithm is particularly well suited for space applications involving very flexible robot designs. The ability to incorporate compensation for link flexion on earth may prove to be a very useful tool in the development and testing of such robots.

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Omnicon - The Self-Aligning Space Connector

May 1, 1988

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Abstract

This paper describes a NASA patented self-aligning electrical connector that was invented in December, 1980, by Keith Clark and Donald R. Scott, employees of NASA/MSFC.

The inventors and author of this paper feel that this connector has a tremendous application not only as applied to Robotics and the Space Station but in many other Military and Industrial applications.

This invention has gone practically unnoticed by the space related industry. Environmental Components, Inc., a local space technology oriented corporation has applied for exclusive manufacturing rights and proposes to convert the invention into a product available for use by the military, industrial and space industry.

Introduction

The self-aligning electrical connector as designed for Space and Robotic applications has been named the Omnicon. The Omnicon is in the process of being copyrighted.

The Omnicon was invented by Keith Clark and Donald R. Scott of NASA/MSFC.

Throughout military and aerospace history many liftoff-launch holds or delays in launch schedules have been traced to improper electrical connections such as connector contact resistance and bent connector pins due to connector misalignment and high dimensional tolerances. These dimensional tolerances of the standard pin and socket approach when used in space exaggerate the problems experienced on ground several times. It has been said that manipulating small items such as connectors in space with space suit gloves on, can be likened to trying to button a shirt button with boxing gloves on! In the case of space robots or manipulator arms the task of orienting and mating two electrical systems becomes even more difficult. The inventors of the self-aligning space connector no doubt had all these problems in mind and have been disappointed in the lack of interest from the aerospace community and the non use of this invention in response to a formidable problem. This lack of response is no doubt due to the lack of publicity and the design required to transform the patent drawings to manufacturing drawings necessary for the fabrication of a finished product.

Environmental Components, Inc. hopes to overcome these obstacles by publicizing this connector, and by producing prototypes and usuable hardware in direct response to the needs of the various military and aerospace companies throughout the world. Our start will be the introduction of this connector at today's symposium.

Environmental Components, Inc. solicits those companies or Government agencies with possible applications and or problems to let them be known. At this time a standard line connector with predetermined plug receptacle, pin arrangements and shell sizes has not been established. Every order will be a special one until some standardization can be established. Environmental Components plans to specialize in custom applications of this connector.

Applications

The viewgraph presents pictorially the many applications of the Omnicon. The Omnicon is currently in the early stages of development. We have built a simple demonstration model and anticipate being able to provide the connectors in limited quantities for use in approximately twelve months.

Omnicon's applications are as broad as current applications for conventional connectors, with the advantage of being easier to use. The Omnicon was invented specifically for use in space. The Omnicon is simple to operate even under Zero G conditions. Many electrical connections are necessary, for example during the exchange and ferrying of modules from an orbiting platform or space station by the orbital servicer vehicle. In space the precise alignment in both the rotational and translational directions necessary for conventional connectors is difficult and troublesome, and simplified through the use of the Omnicon.

Design Considerations

The Omnicon can be fabricated from a wide variety of materials such as thermo setting plastics, Lexan, RTV Silicones, Composites, Teflon, Ceramics, Stainless Steel, Aluminum, etc. therefore making possible a connector that will operate under a wide range of environmental conditions such as

Temp. -400 degrees to +1000 degrees F
Humidity 0 - 100% R.H.
Radiation High Neutron Flux Density
Vibration High G^2 vs Hz Capabilities
High Current carrying capabilities

The present Omnicon design requires that the power be off before mating, otherwise undesireable contacts or switching might occur. To overcome this limitation, Environmental Components has designed an option of an Omnicon with a switching action that occurs during the 90 degree rotation of the plug locking it into the receptacle. This is a rotary wiping switch action located either in the plug or if desired in the receptacle which disconnects the connector contacts during the mating action. Omnicon connector design requiring large numbers of circuits are available. This is possible by resorting to the segmented contact design which would require plug orientation in the radial plane. For instance, an Omnicon with seven (7) circular contacts could be converted to a twenty eight (28) contact design by segmenting the seven ring contacts by four and not allowing the plug to rotate with respect to the receptacle.

Basic Design Concepts

The Omnicon design will be more readily understood by referring to the following figures and explanations.

Fig. 1 is a perspective view illustrating application of the Omnicon to a space vehicle and removable module making electrical connection there between.

Fig. 2 is a perspective view illustrating the plug and receptacle components of the Omnicon in a disconnected configuration;

Fig. 2A is a partial sectional view in elevation illustrating the mechanical connection of the plug and receptacle components to their respective module or vehicle surface.

Fig. 3 is a perspective view of the receptacle component which is partially cut away to illustrate the annular contact rings and their connection to the receptacle component;

Fig. 3A is a perspective view of the annular mating ring of the receptacle component having segmented spring-loaded contact surfaces;

Fig. 3B is a sectional view of the receptacle contact ring illustrated in Fig. 3A illustrating the spring-loaded feature of the mating ring;

Fig. 4 is a perspective view of the plug component of the invention in section illustrating the contact rings and their connection; and

Fig. 4A is a perspective view of a contact ring of the plug component.

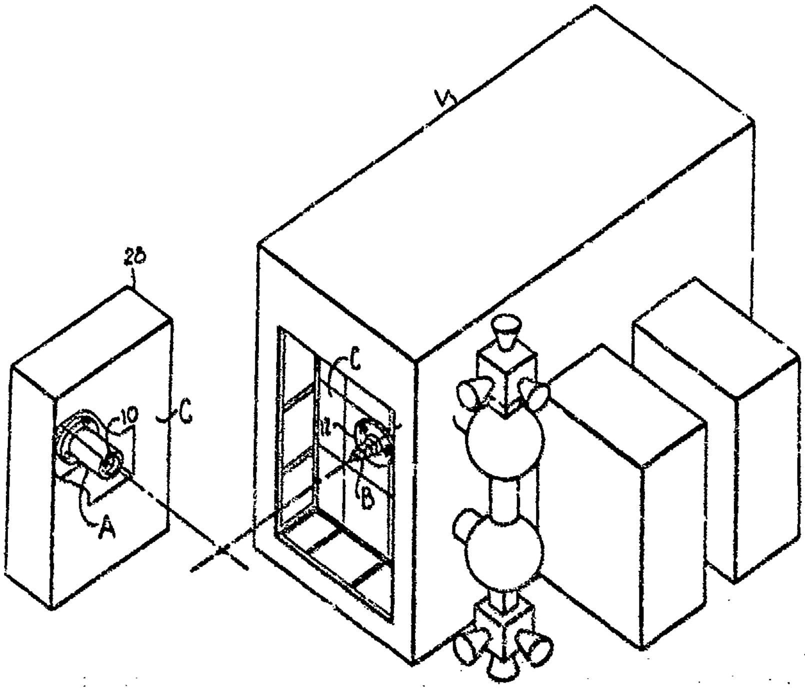
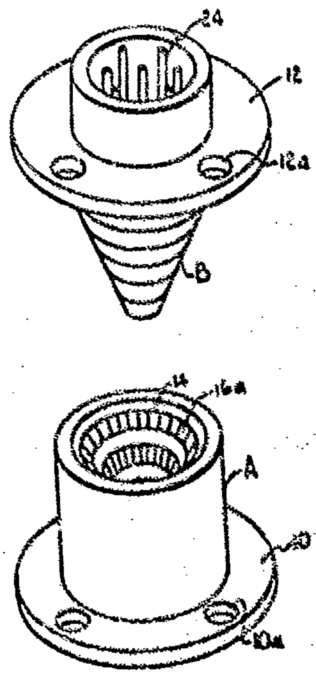


fig 1



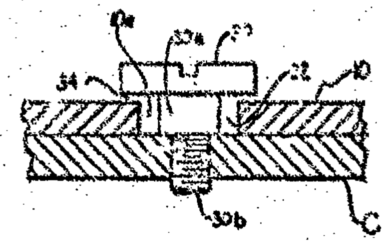


fig. 2a

fig. 2

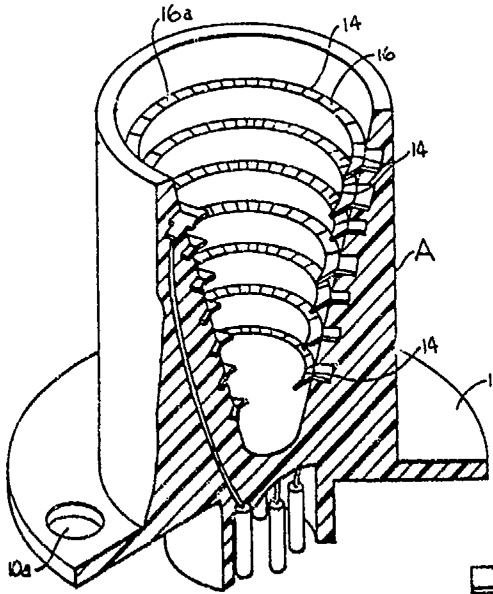


fig 3

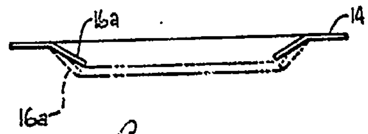


fig 3b

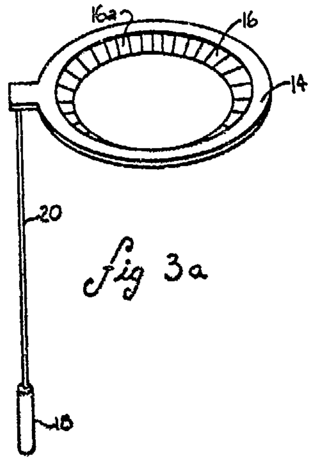


fig 3a

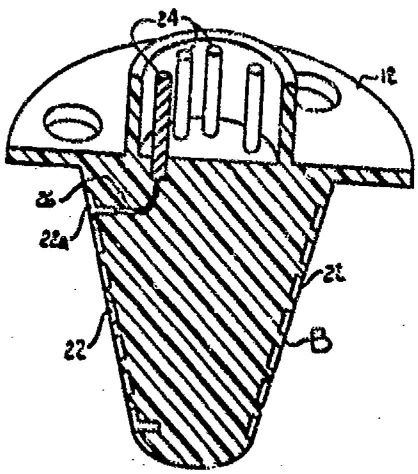


fig 4

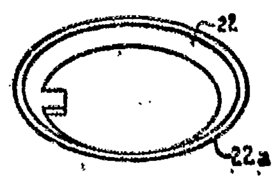


fig 4a

Conclusion

Omnicon is a unique connector that simplifies connect/disconnect operations in "0" gravity environments as well as in commercial operations in normal gravity situations that now require slower, more difficult alignment to make connection.

Conventional Connectors:

Precise Alignment

Visual contact must be made

Pins often bend

Not designed for repeated connect/disconnect operations

Omnicon Connectors:

Omnicon is designed for repeated and easy connect/disconnect

Bands replace pins

Visual contact is not required

Aligns itself

FLUID DISCONNECTS FOR AUTOMATED AND ROBOTIC SPACECRAFT SERVICING

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ABSTRACT

This paper documents the development of an advanced rotary shut-off (RSO) disconnect technology specifically designed for EVA, telerobotic, robotic and automated spacecraft servicing. The standardized internal elements and their relative merits are described. Various disconnect configurations such as interface mounted, manual, semi-automatic and fully automatic are discussed. EVA and robotic operational demonstrations of manual and semi-automatic units are reviewed. In addition, the development of a fully automated, multi-line, spacecraft to spacecraft resupply interface will be described.

INTRODUCTION

The goals of the U.S. civilian and military space programs have created a need for large, complex, long-life spacecraft. The Orbital Maneuvering Vehicle (OMV), Orbital Transfer Vehicle (OTV), Great Observatories, Space Station and its free flying platforms are examples of NASA programs that fit this category. DoD applications have been summarized by the Space Assembly, Maintenance and Servicing Studies (SAMSS) which have called for a space based infrastructure to support future military orbital systems. This emerging generation of spacecraft has spawned a new set of design drivers for their fluid systems and components. On-orbit erectability, maintainability, expandability and consumable resupply are evolving requirements that cannot be achieved through traditional all-welded fluid system designs. The ability to safely make and break connections without fluid loss is inherent to meeting these requirements. It is anticipated that disconnects will be used in large numbers to facilitate this capability.

An integrated mix of human, robotic and automated capabilities will be used to effect these on-orbit activities. It is essential that manual disconnects be user friendly to both a fully suited astronaut using standard tools and a robot equipped with a general purpose end effector. Fully automated connector systems although nominally autonomous, should be manually operable by both astronauts and robots as an ultimate back-up to redundant internal power.

RATIONALE FOR THE WORK

Moog has undertaken an evaluation of the prevailing disconnect technology against the anticipated requirements of spacecraft servicing applications. We found that fluid disconnect technology embodied by commonly used models was relatively stagnant with most manufacturers using similar designs.

To thoroughly understand this technology, we designed, built and tested some poppet type disconnects. We then compared them to commercially available "aerospace quality" disconnects. Although we were successful at stretching the poppet type disconnect technology to the limit, we found that they have an inherent pressure drop and a tendency toward O-ring blow out at higher pressures. In addition, the poppet seals were vulnerable to leakage due to contamination. As the relatively large poppet seals closed, contamination could be trapped between the seal and seat causing leakage.

Actuation and latching mechanisms were also evaluated. Most prevalent are the snap together/quick release type. To engage, the two halves are axially inserted until both are open and latched together. They offer no mechanical advantage in overcoming pressure induced separation forces, thus they cannot be mated when internally pressurized. This is a severe operational limitation requiring the system to be shut down and depressurized before connections can be made. During disconnection, the trigger action of the quick release mechanism sets the disengagement sequence in motion. Under pressure, the two halves are energetically and uncontrollably driven apart. This imparts a sudden force that could damage a robotic operator or jar a weightless human operator. Should a seal fail to seat properly, there is no provision to abort the disengagement process, thus sudden leakage would occur without the ability to reconnect.

The other common method of joining and holding the disconnect halves together is a simple screw thread. This approach is cumbersome and fatiguing for an astronaut to operate in addition to requiring a large wrench not currently contemplated as a standard tool. When operated by a robot, alignment would be critical to engage the threads without cross-threading and complex movements would be required to rotate the sleeve.

As a result of this evaluation, we determined that the prevailing disconnect designs were inappropriate for spacecraft servicing applications and an advance in technology was required. To satisfy this perceived need, Moog initiated an IR&D Program to develop an appropriate fluid disconnect technology. This ultimately led to the development of an alternative disconnect technology called a rotary shut-off (RSO) disconnect.

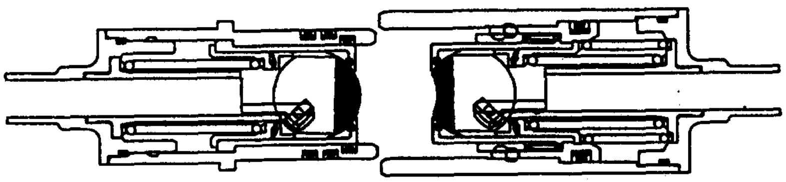
In addition to Moog's IR&D effort, Boeing Aerospace Company in Huntsville, Alabama, evaluated disconnects for potential propulsion system resupply applications. Boeing conducted an extensive test program comparing a variety of poppet type disconnects including ours and found them all less than optimal. Boeing subsequently conducted a competitive procurement for a minimum spill fluid connector suitable for eventual Space Station hydrazine resupply applications. Based on their earlier evaluation, Boeing selected a design based on Moog's RSO disconnect technology.

ROTARY SHUT-OFF (RSO) DISCONNECT TECHNOLOGY

The RSO disconnect is a modular design. The core assembly contains the flow control devices and is common to all the various disconnect configurations. This is possible because the flow control devices are operated by simple axial engagement or disengagement of the disconnect halves regardless of how it is accomplished.

In essence, the RSO disconnect is a patented, self-sealing device which, when engaged, seals the interface and opens an unobstructed flow path across it. The RSO disconnect utilizes spherical valving elements in lieu of traditional poppets. By axially engaging the male and female housing, a sequence of events is completed which forms a straight-through, smooth-walled flow path. This engagement process is detailed in Figure 1.

A)



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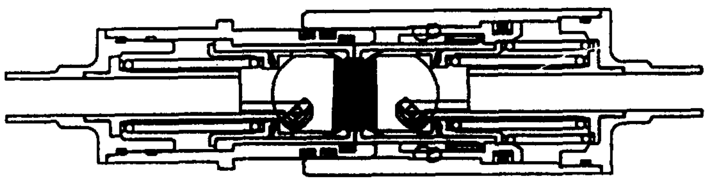

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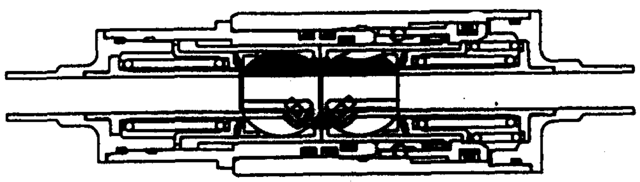


Figure 1: RSO Disconnect Core Operation
(Actuation and Latching Mechanism Deleted for Clarity)

In Figure 1a, the two housings are completely disengaged and roughly axially aligned. The spherical valving elements in both halves are closed and sealed. To mate the disconnect, the two halves are axially engaged. The redundant interface seals engage before the valve cartridges make contact as shown in Figure 1b. At this point, the spherical valving elements are still closed and sealed. By simply continuing axial engagement, the spherical valving element are positively driven open. At full engagement, as shown in Figure 1c, the mated coupling forms a straight-through, smooth-walled flow path across the interface. Demating is accomplished by simply reversing the process and disengaging the disconnect halves. This drives the spherical valving elements closed and breaks the interface seals without spillage of the internal fluid.

The RSO disconnect has the following features:

- Safety: Designs available commensurate with a critical or catastrophic hazard in a man-rated system.
- Reliability: Estimated mean time between failures of 5.4×10^9 hours.
- Cycle Life: Demonstrated cycle life in excess of 1,000 mate/demate cycles.
- Pressure: Operable under full system operating pressure.
- Pressure Drop: Unobstructed flow path for minimal pressure drop.
- Spillage: Fluid volume released upon disconnection as low as $0.19\ cm^3$.
- Leakage: Zero liquid leakage. Easily meets typical leakage rate requirement of 1.0×10^{-6} sccs GHe.
- Mass: High performance to mass ratio.

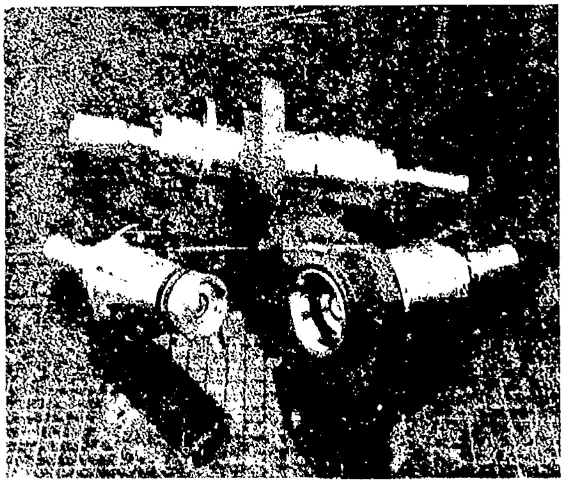
An extensive in-house test program has been undertaken by Moog in addition to evaluation conducted by potential users. NASA/MSFC, NASA/GSFC, NASA/LaRC, NASA/JSC, NASA/KSC, Boeing, McDonnell Douglas, Grumman, Lockheed, OAO and MBB/Erno have all verified various features of the RSO disconnect.

INTERFACE MOUNTED DISCONNECTS

Interface mounted disconnects are specifically designed to be incorporated into module interfaces and automated connector carriers. These disconnects use the standard RSO core assembly discussed in the previous section. Externally these units are quite simple with no soft dock, actuation or latching mechanism. In order to accommodate misalignment between halves when connected, these connectors feature a compliance mechanism.

A major application for disconnects of this type is in interfaces for spacecraft subsystems and attached payloads packaged as orbital replaceable units (ORU). Figure 2 shows a set of Moog RSO disconnects and a typical ORU. The ORU shown is an MBB/Erno unit under development for the European Retrievable Carrier (EURECA) platform. Similar ORU's are being developed by GE-Astro for the Space Station free-flying platform. In both cases, Moog interface mounted disconnects are being used to connect the ORU to the thermal management system of the host spacecraft.

GE-Astro has demonstrated several sophisticated robotic ORU exchanges using mock-ups containing the disconnects pictured in Figure 2. During ORU exchange, the fluid connections were made as a by-product of ORU installation and their presence was transparent to the user.



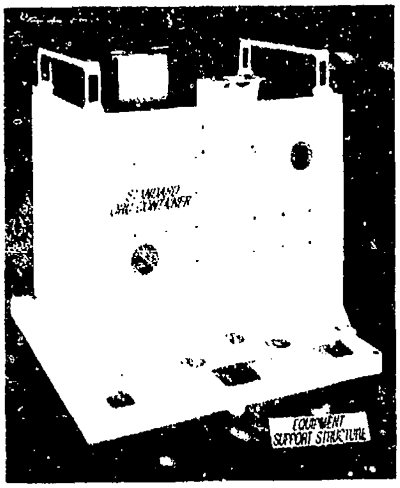


Figure 2: Interface Mounted Disconnects and Typical ORU

Moog has proposed an advanced RSO disconnect design to TRW for the OMV. One replacement coupling will be used to connect each of four Reaction Control System (RCS) modules to a central bus. The function of the replacement couplings close and seal hydrazine propellant on both sides of the interface as the RCS module is removed from the OMV structure. Since the RCS module is an orbital replaceable unit to be exchanged in the shuttle bay, the coupling is designed to shuttle bay safety requirements. The OMV replacement coupling represents the state of the art in RSO disconnects. It is designed for highly reliable, safe operation. The following is a summary of its features:

- Spillage - less than 1.0 cc upon disconnection.
- Pressure Drop - less than 20 psid at 0.34 lbm/sec hydrazine
- Single potential external leak path.
- Three mechanically independent interrupts against external leakage when connected.
- Two interrupts against external leakage when disconnected (system provides third interrupt).
- No dynamic seals.
- Allowable misalignment - ±0.50° angular, ±0.025" axial offset.
- No flex hoses required.
- Propellant wetted materials - CRES, Teflon, EPR (seals).

MANUAL RSO DISCONNECTS

The basic objective of Moog's IR&D program was to produce a device capable of making a line connection that when broken, closed and sealed. Single line and multi-line units designed to accomplish this have been design, b[illegible]t and tested both in house and by prospective users. A significant portion of our effort has been allocated to the development of a safe, reliable actuation and latching mechanism. Our goal was to design a fluid disconnect, the operation of which was both robotic and EVA user friendly. The result is our soft dock/hard dock approach to manual mating exemplified by the single line unit shown in Figure 3.

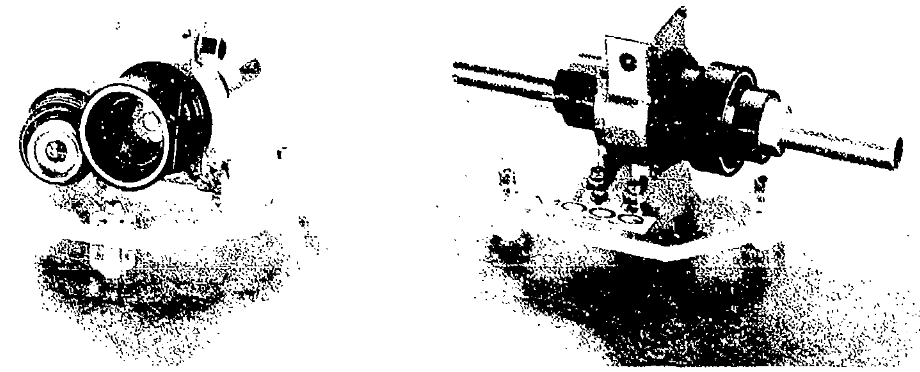


Figure 3: Manual Single-Line RSO Disconnect

The female half is assumed to be rigidly attached to the spacecraft structure and is hard lined into the system piping. The male half is typically attached to the system piping via a flex hose. To make a connection, the male half is axially inserted into the female half until a soft dock is achieved. This requires a maximum force of 20 lbf. At this point, the male half is captured and can be released without floating out of position. A standard manual or motorized ratchet tool with a 7/16" socket is then used to drive the connector to the fully mated position. Since the actuation and latching mechanism is based on threaded sleeves, a significant mechanical advantage can be brought to bear. Actual test data shows that the maximum torque input required, with the disconnect pressurized to 620 psig, is only 3.5 ft-lbs. The threaded sleeves are not back-driveable, thus engagement/disengagement can be safely aborted or reversed at any point in the sequence. This activity has been demonstrated by both astronauts and robots.

A Moog single-line RSO disconnect has been evaluated against the unique ergonomic requirements of on-orbit, EVA operations by the Crew and Thermal Systems branch at NASA/JSC. To this end, a connector demonstration test article has been successfully flown several times in NASA's KC-135 microgravity facility. Astronauts in fully pressurized EMU's have verified the EVA user friendliness of the RSO disconnect using standard manual and hand held motorized tools. An astronaut is shown in Figure 4 operating an RSO disconnect during a recent flight. Note that once soft docked, the astronaut is free to use both hands to operate the tool or hold on to "ground".

Figure 4: Astronaut Evaluation of RSO Disconnect

Several government and industry robotics labs are involved in experiments designed to determine if the same RSO disconnect used in the EVA demonstrations is also robot user friendly. Robotics labs at NASA/GSFC, NASA/JSC, NASA/KSC and Boeing are all currently working with the RSO disconnect for this purpose. Boeing's successful demonstration of this capability is shown in Figure 5. For this demonstration, Boeing used a Puma 560 robot equipped with a JR3 Inc. force/moment sensor and a simple gripper type end effector. The end effector was also equipped with a motorized allen wrench.

A)

B)

C)

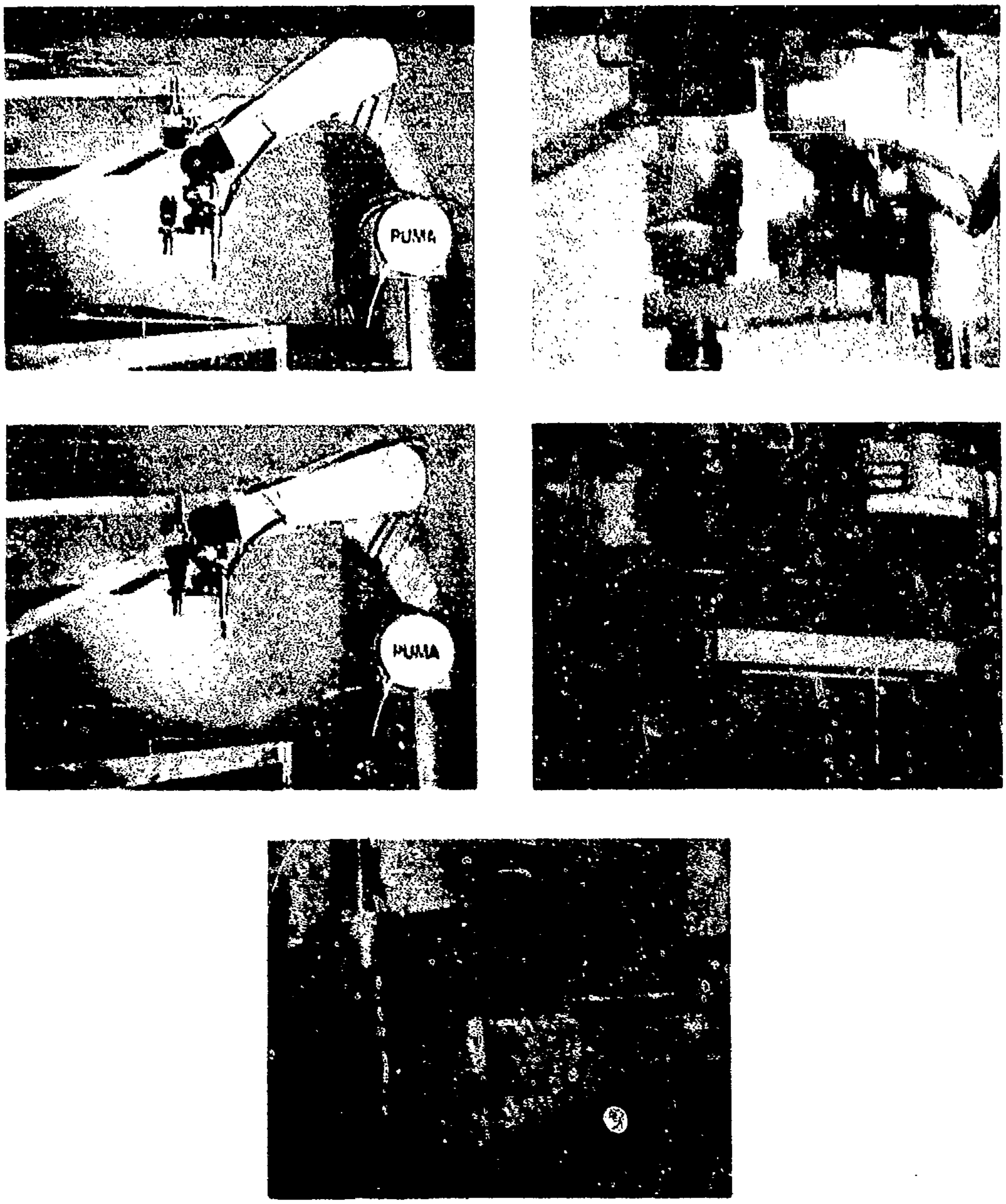


Figure 5: Autonomous Robotic Operation of RSO Disconnect

The robot under autonomous control grasped the male half of the disconnect with the gripper and positioned it roughly coaxial with the female half as shown in Figure 5a. The robot then axially inserted the male half into the female half using X, Y, Z force and torque feedback to "feel" its way in. Using a special algorithm, Boeing engineers were able to soft dock the couplings as shown in Figure 5b using a maximum force of 5 lbf instead of the normal 18 lbf. Using the soft dock feature of the disconnect to hold the male half in place, the robot released it and moved into position to engage the motorized drive tool as shown in Figure 5c. If an end effector without an integral motorized tool had been used, the robot could just as easily have moved to a tool caddy to pick one up. The robot then inserted the tool into the drive socket and drove the disconnect into the fully mated position by rotating the tool clockwise. The fully mated or hard docked position was determined by sensing torque. Removal of the tool completed the task.

Demating was also demonstrated. This was accomplished by simply reversing the mating sequence. The interesting aspect of this task was the robot could pause at the soft dock position, disengage the tool and move to grasp the male half without it prematurely separating from the female half. The robot then axially extracted the male half from the female half to complete the demate task.

Significant time savings can be realized where multiple connections must be made by using a two-armed robot. In this scenario, the first robot will grasp and soft dock the disconnect. As it moves to grasp the next disconnect, the second arm will engage a motorized hand tool and drive the first disconnect to the fully mated position. Time savings are realized due to overlapping the steps as well as eliminating time required to exchange or reposition tools. It is estimated that mating/demating time can be trimmed by 30 percent using this method.

This IR&D program has resulted in Moog being awarded a major development program contract by NASA/JSC to develop, qualify and produce a Helium II Orbital Resupply Coupling. This device, shown in Figure 6, will be capable of making a connection between two spacecrafts through which cryogenic helium at 1.8°K can flow. This will allow superfluid helium, which cannot be stored indefinitely, to be resupplied on-orbit. The implication of this is that expensive assets such as infrared telescopes like SIRTF will have an extended useable life span. Heat seepage into the cryogenic helium as it passes through the disconnect is kept to less than 0.08 watt by suspending the cold core inside a vacuum jack with thermal isolators. To prevent the leakage of helium when disconnected, RSO elements will close and seal. When connected, triple redundant interface seals prevent leakage of the liquid helium.

Designed for easy conversion to an interface mounted unit suitable for an automated connector carrier, manual man-rated units wil be built first for the Superfluid Helium On-Orbit Transfer (SHOOT) Shuttle bay experiment. This work is being conducted under Contract Number NAS9-17872.

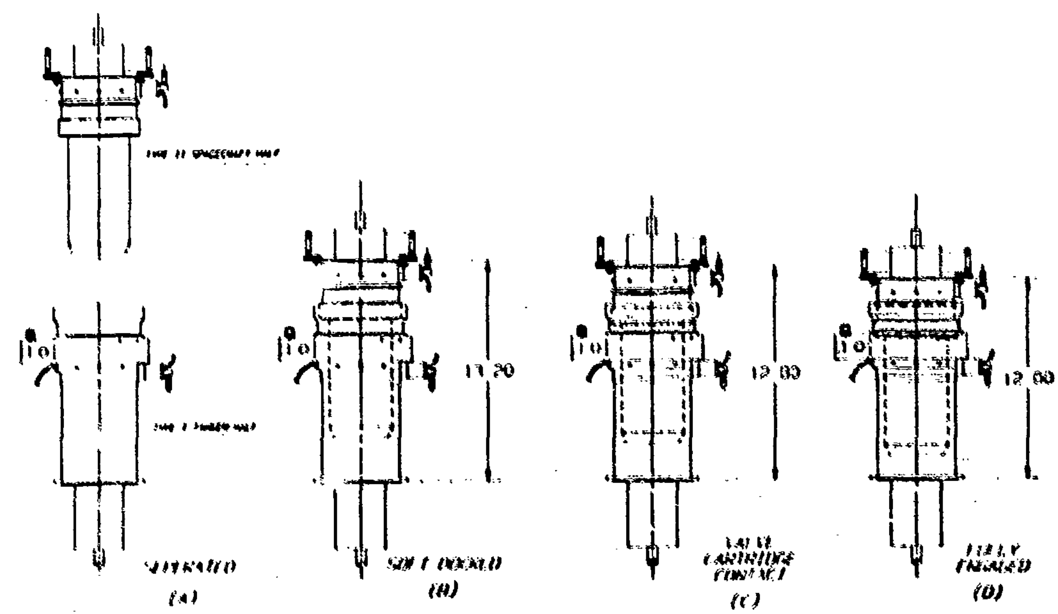


Figure 6: Helium II Orbital Resupply Coupling

SEMI-AUTOMATIC RSO DISCONNECTS

The same soft dock/hard dock approach to mating/demating manual units is used with semi-automatic and multi-line RSO disconnects. The dual-line disconnect/isolation valve shown in Figure 7 is a typical arrangement.

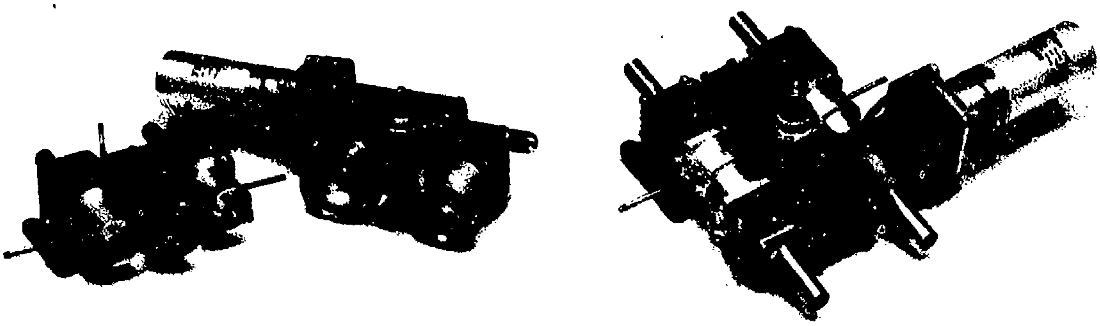


Figure 7: Semi-Automatic Multi-Line RSO Disconnect

Two identical sets of RSO internal elements are arranged in a parallel fashion in a single assembly. The actuator is located between the passages and consists of a screw in the female half that engages a threaded boss in the male half. The threaded boss features a "soft dock" mechanism that initially captures the two halves then guides the threads together without cross threading or the application of an axial force. The screw is driven by a worm/worm gear set with built-in over torque protection. Mechanical inputs are via a 7/16 inch hex drive shaft which is compatible with standard manual or motorized hand held tools.

For semi-automatic operation the optional gear motor drive allows the unit to be remotely operated under full system pressure. This converts the unit into the equivalent of two disconnects and two isolation valves. The manual hex drive shaft provides robotic and EVA compatible manual override. Non-contact switches sense the relative position of the male and female half. All data and power is brought out through the electrical connector.

The integral motor can be used in conjunction with a robotic or EVA astronaut to streamline mating and demating tasks. In this scenario, the robot or astronaut would simply soft dock the disconnect. The integral motor could then be commanded to finish the mating task. This capability increases operational flexibility thereby enhancing the probability of a successful mission.

The dual-line configuration, shown in Figure 7, can also be used to connect feed and return lines for a system segment or provide a modular interface for orbital replaceable units (ORU's). For small to moderate sized components, the disconnect interface can be used as a structural connection. By using the female half as a receptacle and building the male half into a component, it can be converted into a modular component.

A Moog modular component can automatically be isolated from the system upon failure by remotely using the integral motor to close the disconnect interface. The faulty component can then be quickly and easily removed from the system under full system pressure without fluid loss. Dual-line disconnects and modular components are currently being integrated into a prototype Space Station thermal bus system being built by Grumman Space Systems. The merits of this modular approach to fluid system integration will be evaluated during system level testing at NASA/JSC. In addition, evaluation testing will be conducted at NASA/GSFC and NASA/MSFC.

AUTOMATED FLUID INTERFACE SYSTEMS

The ability to make automated multi-line umbilical connections between spacecrafts is crucial to future orbital operations. Potential applications include:

- Consumable Resupply
- Inter-module Umbilical Connections
- Satellite/Platform Servicing
- Attached Payload Interfaces
- OMV/OTV Servicing
- Robotic Ground Servicing Operations
- Shuttle/Station Interface

Moog has undertaken an IR&D project to design, build and test an automated umbilical connector (AUC) system capable of facilitating the above stated operational capabilities. The result of this effort is the AUC shown in Figure 8. This technology demonstration unit is a fully automated, turn-key interface system capable of simultaneously connecting four power, data, liquid, cryogenic or high pressure gas couplings. The AUC consists of a Type I (tanker) half, a Type II (spacecraft) half and an electronic control.

A key element in the design approach to the AUC was the utilization of existing Moog disconnect technology. The disconnects, used are configured as interface mounted RSO disconnects similar to those shown in Figure 2 but specifically designed for use in the AUC.

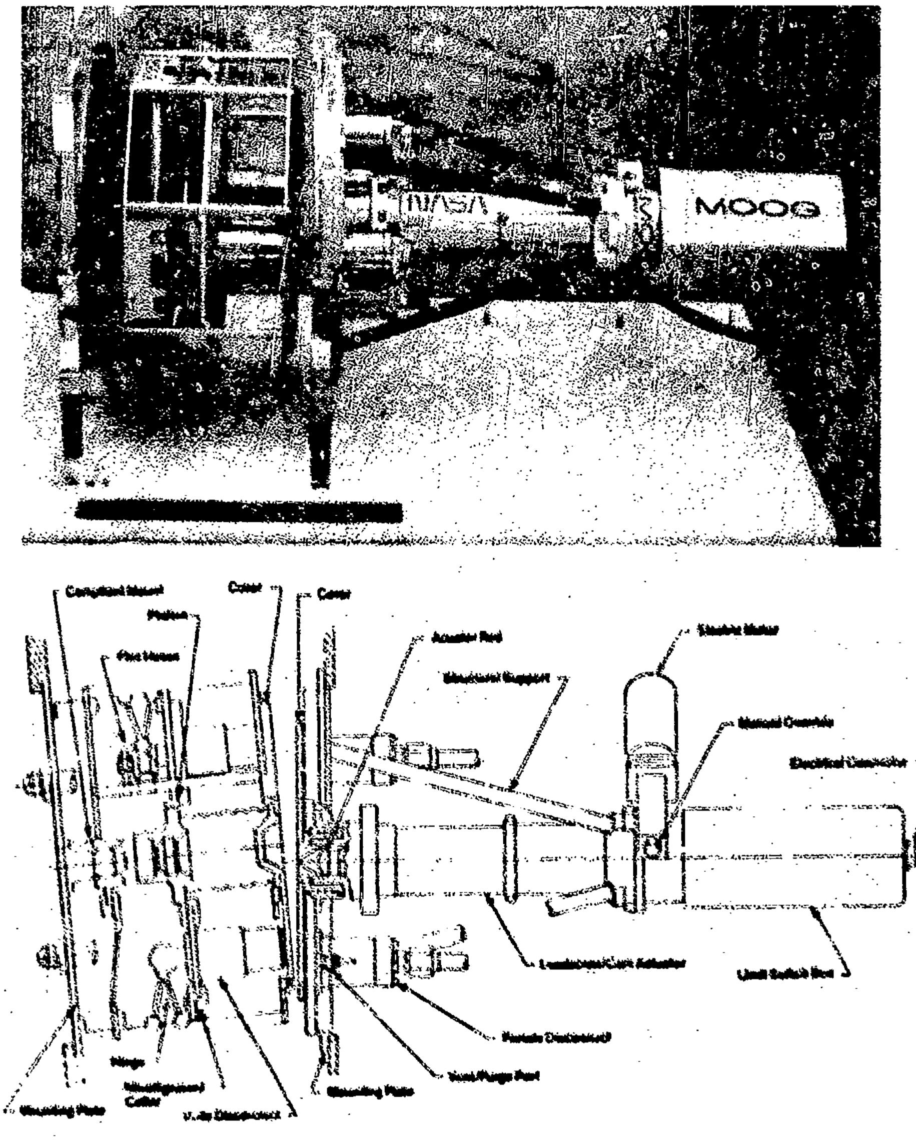


Figure 8: Automated Umbilical Connector

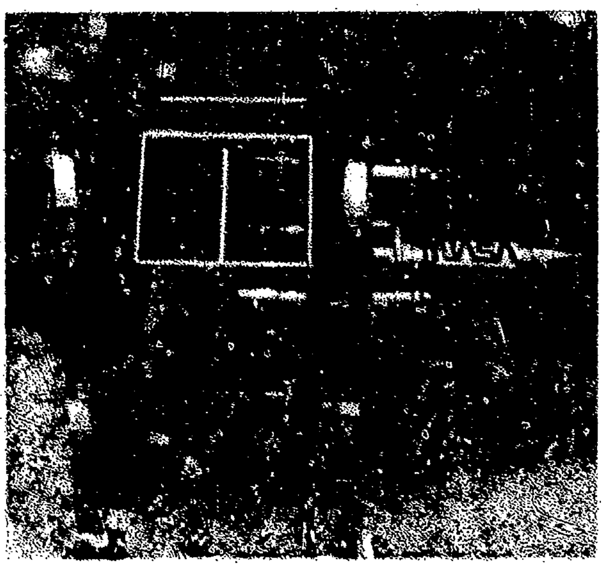
The AUC has the following features:

- Fully automated for remote operation
- Simple electromechanical actuator
- All mechanical functions powered by a single motor
- Simple, reliable open-loop control electronics
- 100 watt nominal power draw
- Manual override in case of motor failure
- Type II half requires no power or sensor data
- Accommodates misalignment
- Connectors mounted in individual misalignment collars
- Automatic covers mechanically interlocked with actuator
- No Type I/Type II contact during docking
- Pressure induced separation forces not transmitted to mounting surfaces
- Configurable with up to four power, data, cryogenic, liquid or high pressure gas connectors.

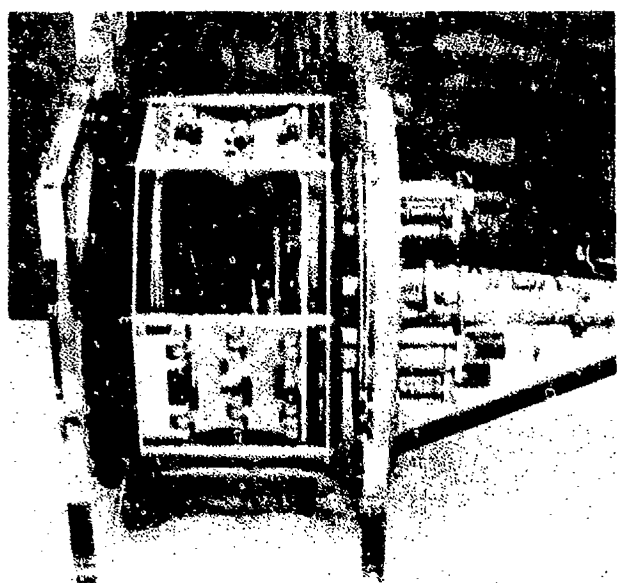
The Type I half of the AUC is a self-contained, modular assembly designed to be normally installed in the tanker spacecraft. All components requiring power and/or control are located in this half. It consists of a structure that supports an electromechanical (EM) actuator, four female RSO disconnect modules and a rotating cover.

The Type II half of the AUC is also a self-contained, modular assembly. This half is electrically passive requiring no power or control and is meant to be mounted on the spacecraft. It consists of a structure that is compliantly mounted to the spacecraft. The rotating cover and a movable platen are, in turn, mounted to this structure. Four male RSO disconnect modules are, in turn, compliantly mounted to the platen.

To engage the AUC the two halves must be positioned within their misalignment envelope as shown in Figure 9a. When the "engage" command is received, the electromechanical actuator extends the actuator rod across the tanker/spacecraft interface. The actuator rod engages the compliant structure of the spacecraft half causing it to align with the thanker half. The actuator rod then rotates 45° locking to the movable platen and rotating both covers open. The actuator automatically retracts driving the disconnects across the exposed interface and into their mating halves. The physical engagement of the disconnect halves automatically drives their rotary shut-off elements open. The AUC is now fully engaged and ready for consumable transfer to take place as shown in Figure 9b.



a) Ready to Engage



B) Engaged

Figure 9: Automated Umbilical Connector Disengaged/Engaged

The "disengage" command causes the actuator to extend until the purge position is reached. This closes the valving elements in the fluid disconnects without breaking the interface seals. At this point, seal integrity can be verified and/or spillage purged. Upon receipt of another "disengage" command the actuator resumes extension breaking the disconnect interface seals and driving the platen back into its retracted position. The actuator then rotates 45° unlocking from the platen and rotating both covers closed. It then withdraws from the spacecraft half of the AUC allowing it to relax back into its original position as shown in Figure 9a. At this point, the connection cycle is complete.

Extensive testing was performed at Moog on this system. The AUC met or exceeded all performance requirements. Test data is summarized in the table below.

Parameter	AUC Test Data Summary
Inlet and Outlet Ports Size:	1/2"
Fluid Compatibility: (other fluids can be accommodated with adjustment)	Hydrazine, Anhydrous Ammonia, Isopropyl Alcohol, Deionized Water, Helium, Nitrogen
Pressure Drop:	0.75 psid at 5.0 gpm H_2O
Operating Pressure: Proof Pressure: Burst Pressure: External Leakage:	500 psig 1000 psig 2000 psig 1.0×10^{-8} sccs GHe @ 500 psig after 1000 cycles
Seals Against External Leakage: Connected Disconnected	 3 1 (seals can be verified)
Spillage Volume:	0.07 cm^3 without purge 0.024 cm^3 with evacuation and GN_2 purge
Temperature:	-65°F to 250°F (not verified)
Misalignment:	0.125" axial and lateral 5.0° angular 1.0° rotary
Envelope: Type I Type II	 13" dia x 22" 13" dia x 8"
Weight: Type I Type II	 16 lbm 18 lbm
Cycle Life:	1000 cycles fully misaligned with two disconnects pressurized to 500 psig

In 1987, Moog completed a contract with Boeing Aerospace Company of Huntsville, Alabama, to provide one Model 50E559 AUC System. This contract was a direct result of our IR&D activity but was separte from it. The device, originally called a Minimum Spill Fluid Connector, was built under an advanced development contract related to Boeing's Space Station Phase "B" study efforts. As such, it was administered as under the auspices of NASA/MSFC.

The objectives for the U.S. civilian and military space program have created a need for disconnects to facilitate on-orbit erectability, maintainability, expandability, consumable resupply and automated fault isolation/recovery in space borne fluid systems. These disconnects must be compatible with the integrated human/robot automation environment envisioned for future orbi erations. Disconnect technologies widely used in the past for other aerospace applications were found to inadequate or undesirable.

In response to this need Moog has developed, under IR&D, an alternative disconnect technology called a rotary shut-off (RSO) disconnect. This new disconnect technology, extensively tested by Moog, NASA and industry, has been shown to be a significant improvement over designs commonly used in the past.

To facilitate on-orbit servicing operations, a safe, convenient and reliable method of manual mating/demating has been developed. Identical units have been verified to be user friendly by both fully suited astronauts and autonomous robots. Semi-automatic disconnects have been shown to not only automate fault isolation and recovery in these systems but also to assist EVA and robotic mating/demating.

A totally automated fluid interface system called an automated umbilical connector (AUC) has been designed, built and tested. The AUC demonstrated the capability to simultaneously make multi-line connections between misaligned spacecraft for liquid and/or gas transfer. The modular design of this technology demonstration hardware was shown to be feasible thus clearing the way for future upgrades with power, data or cryogenic coupling modules.

Through the work overviewed in this paper, Moog has endeavored to develop a connector technology that can be utilized to facilitate solutions to the problems facing the designers of serviceable fluid systems. By specifically designing this hardware for the integrated human ,robot, automation environment of the future we hope to have also simplified the operational aspects of these tasks.

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Development of a Hybrid Simulator for Robotic Manipulators

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ABSTRACT

The military is pursuing the use of robot manipulators and teleoperated manipulators in hostile environments. Implementation has been restricted by the rudimentary control schemes used by current manipulators. Research into improved control schemes for these manipulators has been limited by the lack of simulation capability.

The need for an adequate articulated robot simulation is great due to the problems of safety, money and work space caused by operation of a robot. An accurate simulation can assist in testing different control algorithmins, as well as different trajectory generators. Accurate models of robot arm dynamics have been identified by several groups; however, the effects of friction and drive motor dynamics have not been properly modelled in the past. These torques have important effects on errors generated by the robot.

The PUMA 560 was chosen as a case study because it represents a class of manipulators of interest to the military and because actual PUMA 560 response data was readily available. Once the proper models were installed on a digital computer and shown to be accurate by comparison to PUMA 560 responses, the decision was made to convert the model for use on a SIMSTAR Hybrid Computer. The analog model gives the control engineer greater freedom in choices of controllers to test. It also provides the capability to run realtime man-in-the-loop simulations. This model is again verified by comparison to actual robot arm motions using the same controllers.

The ability to accurately model an articulated manipulator has a significant effect on the robot community. Now, institutions restricted from controller study by the lack of an available manipulator can test state-of-the-art trajectory generators or controllers and feel confident that the simulator results will be borne out when implemented on the manipulator. Also, simulations of applications such as robotic refueling can be accomplished to determine the viability of a particular control scheme.

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Session IV Program B

Guidance, Navigation and Control

Chair: Greg Graham, USAMICOM

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The DARPA Autonomous Land Vehicle: A Phase I Retrospective and a Prospective for the Future

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ABSTRACT

The Autonomous Land Vehicle Pogram (ALV)--part of the DARPA Strategic Computing program, contracted by the U.S. Army Engineer Topographic Laboratory (ETL)--combines advances in computer vision, automatic planning, sensors and advanced computer architecture to create a mobile outdoor robot that can navigate autonomously on and off roads to accomplish a high level goal. Eventual applications include partially autonomous anti-armor and reconnaissance robots for the Army, a Martian rover and more capable mobile robots for the factory.

During the first 2.5-year phase of the ALV program, road following demonstrations were performed in 1985 at speeds of 3 kph over a 1 km straight road and in 1986 at 10 kph over a 4.5 km road that had sharp curves and changing pavement types. In the 1987 demonstration, the vehicle drove at speeds up to 21 kph (average 14.5 kph) over a 4.5 km distance through varying pavement types, road widths and shadows while detecting, modeling and avoiding obstacles using a perceptual system that combined video and laser radar data to locate boundaries in three-dimensions. Also in 1987, the first vision-guided off-road experiments were performed using the Hughes vision and planning system to cover 0.6 km at speeds up to 3 kph over rolling terrain while avoiding ditches, rock outcrops, trees and obstacles as small as one metal fence post.

In Phase II, begining in early 1988 the ALV focus will be on the support of specific scientific experiments for off-road navigation instead of integrated demonstrations of military applications.

Phase I has demonstrated the feasibility of real-time autonomous navigation. It has seen the development of a test vehicle, laboratory and instrumented test areas, the dissemination of data to researchers, the development of a flexible real-time hardware and software architecture, and the development of several workable approaches to real-world, real-time vision and route and path planning. Open research issues include terrain classification and real-time segmentation techniques for images, the use of additional sensors, such as FLIR and MMW, to augment video and laser radar data, the recognition of objects, and passive ranging techniques such as motion or binocular stereo. Major engineering problems include providing enough computer power to support the real-time execution of more robust vision alogrithms and packaging the technology in low power and weight modules for use on space and military vehicles.

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Applications of Automation and Robotics

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DEVELOPMENT OF A MAN-PORTABLE CONTROL UNIT FOR A TELEOPERATED LAND VEHICLE

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ABSTRACT

A man-portable control unit has been designed and fabricated to support teleoperation of a land vehicle. The basic control unit is configured to include the capabilities of mobile platform control, platform location and status display, sensor control and output display, and weapons control, if so desired. When the platform is being driven to a new location, the operator is able to control the platform through basic steering, braking and speed commands, obstacle recognition and avoidance, maneuvering in constricted space, and navigation with visual cues and simple dead-reckoning inputs from the vehicle. While the platform is on station, the human operator is able to perform the functions of surveillance, target recognition, target tracking, and weapons or designator control.

A fully software-driven system has been configured to meet these requirements. All controls and vehicle signals are processed by an on-board micro-processor allowing an easily reconfigurable system. Video information is provided through a set of three CCTV monitors. Graphics and alphanumeric data are provided on a flat panel display. Push buttons, keypad, trackball, throttle lever, and a steering yoke accept operator input. A video cueing system is included to allow automatic processing of the platform video for motion detection during surveillance operations.

The man-portable control unit was developed for application to the Teleoperated Mobile All-Purpose Platform (TMAP) project supported by the U.S. Army Missile Command (MICOM). The control unit has been integrated with the MICOM vehicle system and with a vehicle system at Sandia National Labs.

INTRODUCTION

Sandia National Laboratories (SNL) was tasked with the design and fabrication of a portable control unit for use by the Teleoperated Mobile All-Purpose Platform (TMAP) project. This project, supported by the U.S. Army Missile Command (MICOM), includes contracts with industry to develop complete systems, as well as significant in-house technology base developments. The overall project goal is the development of a small, low cost, lightweight robotic system which could provide the mobility and control subsystems for a variety of battlefield activities. The intended applications include sentry and scout roles, courier or decoy duty, target designation for longer range weapons, and possibly explosive ordnance disposal. The system was also initially configured to mount, emplace, and operate individual and crew served infantry weapons.

The Sandia control unit allows the operator to maneuver the mobile platform and to operate sensors, target designators, or weapons. Feedback from the platform provides system status, video and audio information, and platform location. The control unit is configured to be fully software driven so that it can be interfaced to a variety of system hardware. For the TMAP project, the platform, navigation equipment, and sensors, as well as the command data link, are being defined and supplied by MICOM [1]. The control unit can also be easily adapted to any of the other systems existing at Sandia [2] or to contractor developed platforms.

CONTROL UNIT DESIGN

The control unit consists of a vertical display panel and a horizontal control panel as shown in Figure 1. All of the electronics (except for the communications interface) are included in

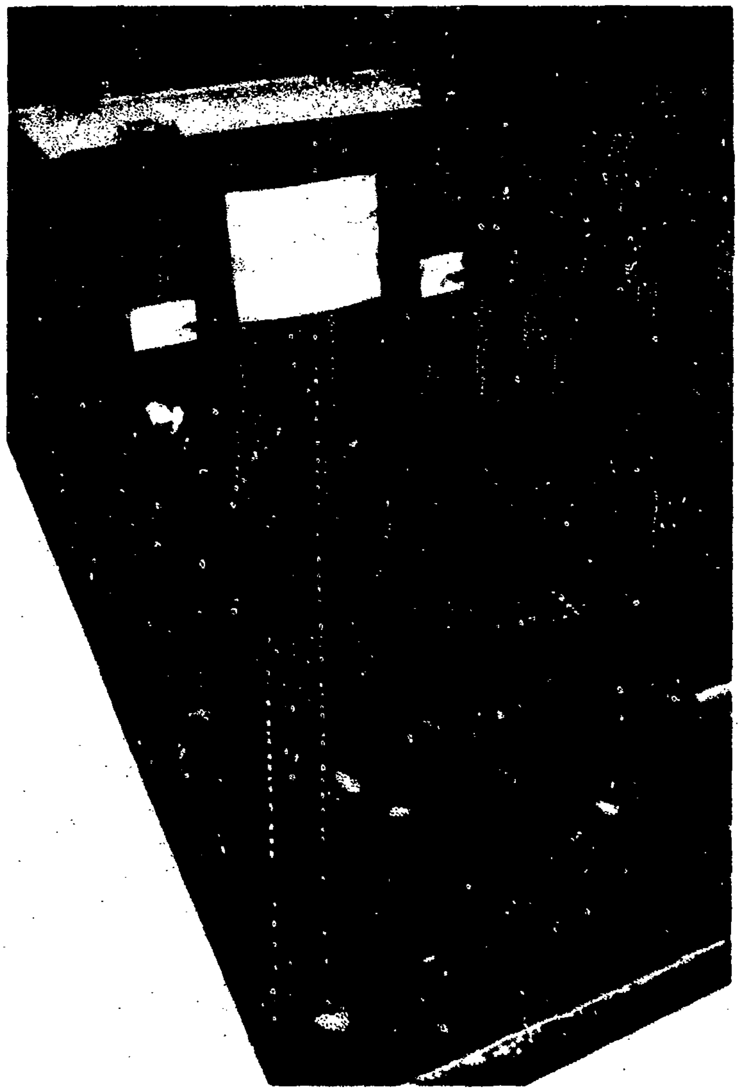

FIGURE 1 - TMAP CONTROL UNIT

the volume behind the panels. For transport, the control yoke folds into the lid of the box, leaving a cube approximately 22 inches on a side. Since commercially available hardware was chosen for system fabrication, significant size and weight reduction could be achieved through dedicated design.

SYSTEM OPERATION

The Sandia control unit is designed to allow effective operation in three different modes. These modes include listening (sensor operation), driving (vehicle mobility), and fighting (weapons control). In the listening mode, capabilities include control of the turret, camera selection, camera zoom, motion detector setup and control, and navigation initialization. Driving mode offers the vehicle commands of steering, throttle/brake, camera selection and zoom, vehicle forward/reverse, and parking brake. The weapons mode allows choice of camera and selection, arm, and fire of individual weapons. Provision is also being made for a range finder in listening and fighting modes.

Navigation capabilities are derived from information supplied by the vehicle. The presently available data includes vehicle heading and distance traveled. This data is stored in the control unit for presentation to the operator. This presentation can be done in several different ways. The position of the vehicle can be referenced to its starting location or to a selected destination by range and bearing. Vectors indicating direction to "home" and "destination" can be displayed referenced to present vehicle heading. Standard military grid map references can be generated for comparison to operator-entered home and destination grid references. Maps of vehicle travel can also be displayed.

VIDEO CUEING

Sandia National Laboratories Exploratory Systems Development Division 9133 has developed and implemented a video motion detection algorithm which processes video input to determine motion along a preselected path. The path is specified by a chain of boxes which can be positioned by the operator in the selected field-of-view of the camera. The size of the boxes can be adjusted so that they approximate the size of the anticipated target. Only the portion of the scene enclosed in the boxes is processed. Movement in other areas of the scene is ignored. Figure 2 illustrates a typical video screen setup.

The algorithm used for motion detection consists of the three major operations of change--detection, grouping, and tracking. This is illustrated in Figure 3. The change detector looks for differences between the current image and a reference image. These are grouped together so that all neighboring changes can be handled as a single entity. The tracking algorithm then looks for purposeful movement of these changes. That is, movement must be detected over a reasonable distance along the selected track for an alarm to be generated. Once an alarm has been registered, both a video and an audio signal are given. These signals continue until the object has left the scene or until the operator intervenes.

FIGURE 2 - VMD PATH SETUP

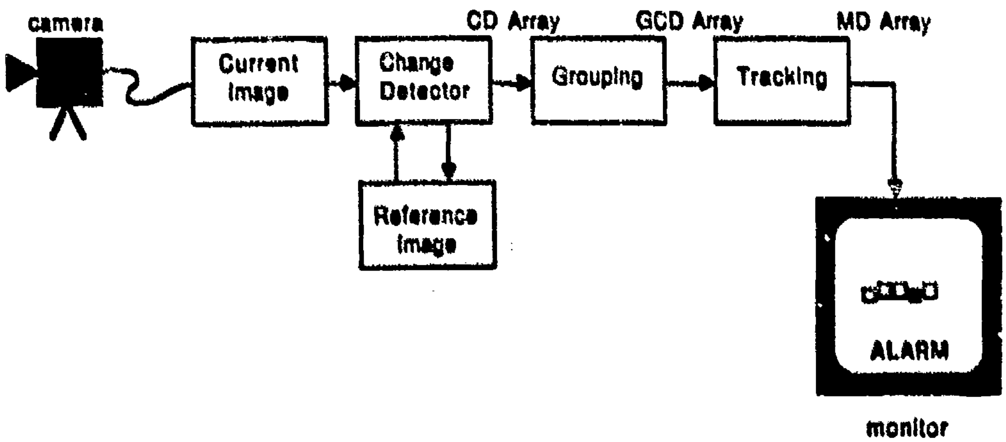

FIGURE 3 - VMD FUNCTIONAL BLOCK DIAGRAM

OPERATOR INTERFACE

The operator interface hardware includes three video screens, graphics display panel, keypad, throttle lever, trackball and control yoke. The video screens and video brightness and contrast controls are mounted on the control unit vertical panel. A 9-inch color monitor (centered in the panel) provides the main display. This monitor may be used to show video from the platform cameras which may include the main mobility camera, a weapons-aiming camera, or a low light level surveillance camera. Two small 4-inch black and white monitors are mounted on each side of the main monitor. These monitors are used to display the output of the driving cameras mounted next to the primary mobility camera on the MICOM TMAP vehicle. The operator controls are on the horizontal panel (illustrated in Figure 4). The graphics display, in the upper section of the panel, allows presentation of detailed status information as well as positional data derived from the platform dead reckoning system. This display panel is surrounded by push buttons. The function of each push button is determined by the mode of operation as will be discussed below. The control yoke is the operator input device for steering commands while driving and turret azimuth and elevation commands when in the listening or fighting modes. The throttle lever provides brake/throttle input while driving. The keyboard and trackball are provided for input of data such as video cuing system setup, map coordinates, map details, and target location selection.

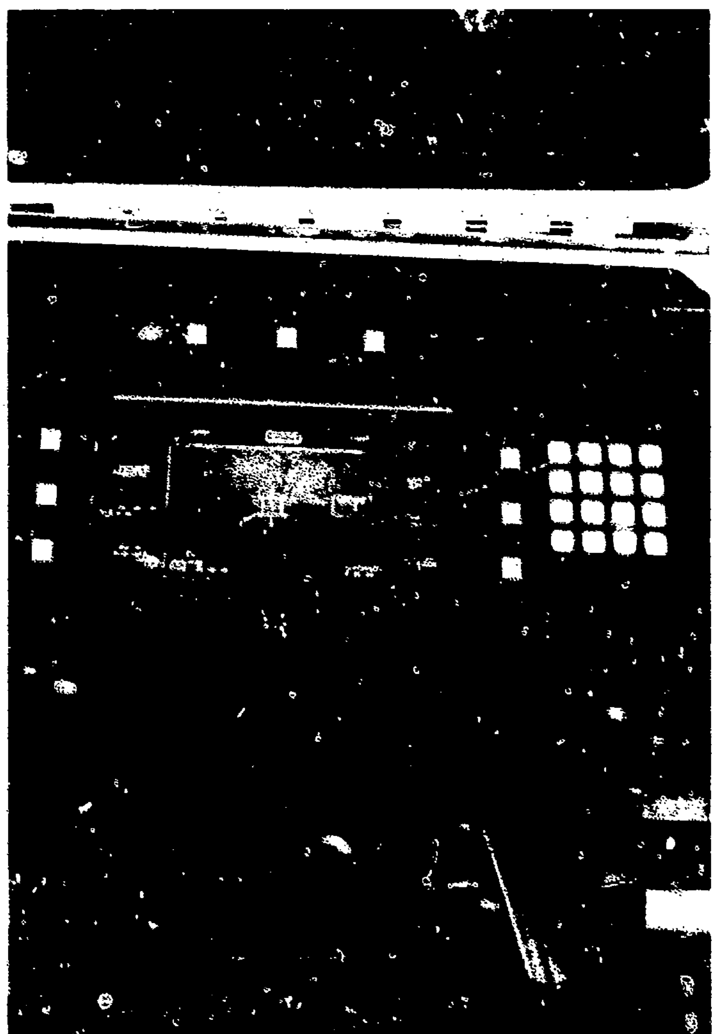

FIGURE 4 - CONTROL UNIT HORIZONTAL PANEL

The selection of a control yoke was based on experimentation using an existing Sandia vehicle. Driving studies were conducted using both a joystick and a simple H-shaped control yoke. (A steering wheel was not tested because it was thought to be too bulky for use in a portable control unit.) In this experimentation, operators drove a small teleoperated vehicle over an off-road course consisting largely of motorcycle trails. The consensus of the operators was that the control yoke was generally easier to use than the joystick. A commercially available control yoke has therefore been incorporated into the control unit design. In addition to steering angle, the selected yoke allows elevation control. There are also finger triggers and thumb push buttons which allow for incorporation of a "deadman" switch.

When the control unit is first powered up, the system is put into the Listening (surveillance) mode, and the operator is presented with the information shown in Figure 5. This information is contained on the graphics display and the associated nine function buttons surrounding the display (shown in the shaded regions of the Figure). The function buttons are not labeled in a permanent manner, but have functions described by the word or words nearest each button at the periphery of the graphics display. In Figure 5, the top three function buttons are used to engage the three main modes of Listening, Driving, and Fighting. The Figure indicates that the system is currently in Listening mode because of the rectangle drawn around the word "Listening." The six buttons on each side of the display can be used to engage subfeatures of the Listening mode. This common theme of having the three major mode selections on the top three buttons, with submodes on the side buttons, is carried throughout all the modes of the system.

If the operator were to press the top center button ("Drive"), the screen would immediately change to that in Figure 6. Note that the word "Driving" is now surrounded by a rectangle to indicate that the current mode is Driving. The word itself also changes from the verb "Drive" to the adjective "Driving," a further indicator of the current mode. The six submode buttons change to subfunctions appropriate to the Driving mode (except for the camera select button, which is used in both Driving and Listening modes). In the center of the display, an icon showing the vehicle appears, always pointing upward with arrows pointing to the next navigational waypoint destination and to home base.

In addition to the changes that happen on the graphics display, several other actions take place when the operator presses the "Drive" button. The first is that the control unit commands the vehicle's camera turret to rotate as necessary to point forward and to lock in that position. The other changes that take place are that the control yoke is interpreted as a steering control, and the T-handle is interpreted as a throttle/brake control. The operator may now drive the vehicle by slowly pushing the T-handle forward until the brake disengages and power begins to be applied to the vehicle drive motors.

Like the changes that happened when the operator pressed the "Drive" button, pressing a button other than "Drive" would also have effected changes to the graphics display, the interpretation of the function buttons, and to the interpretation of the operator controls.

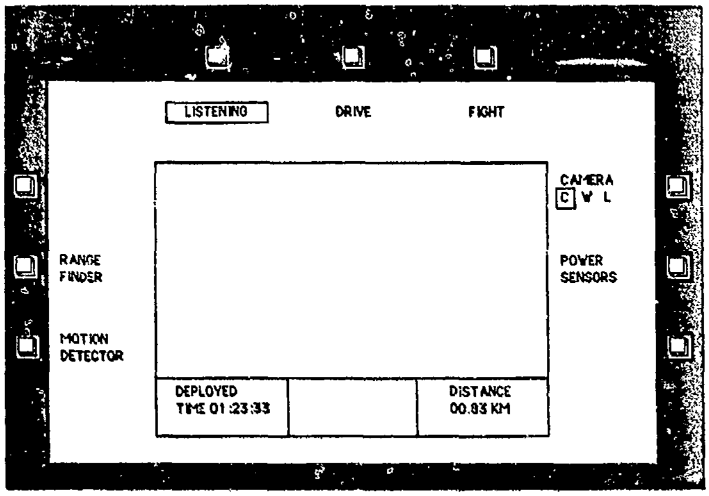

FIGURE 5 - LISTENING MODE GRAPHICS DISPLAY

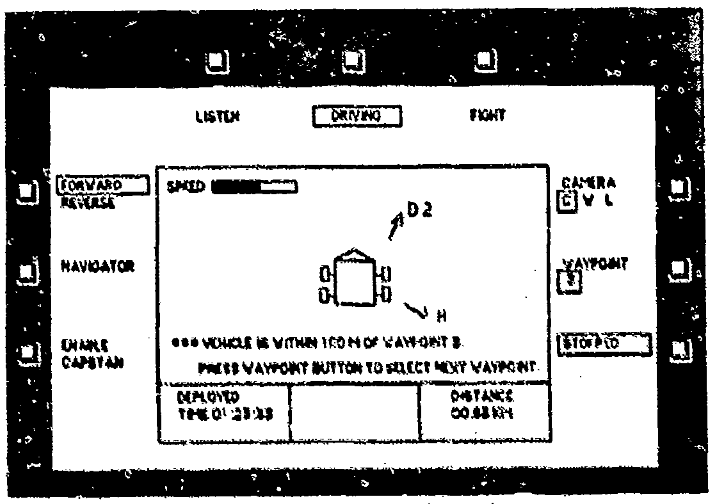

FIGURE 6 - DRIVING MODE GRAPHICS DISPLAY

SYSTEM DESIGN

In many previous vehicle control units, there was little need for software in the system, as the operator controls were "hard wired" to the vehicle systems (albeit with a communications system of some sort in between). However, in the TMAP control unit, the operator's controls (such as the control yoke, throttle lever, and push buttons) and the unit's communications outputs are not hard wired together, but are linked by software through a computer. The continuous controls (like the control yoke) supply analog voltages which, after conversion by the analog-to-digital input board, are simply memory-mapped input ports to the CPU. The binary operator inputs (push buttons) are buffered by the digital I/O board and are also input ports. The output to and inputs from the communications system are likewise simply I/O ports for the CPU. Thus, the interpretation of the meaning of a particular operator input is made entirely by software and is immediately redefinable. This allows a given control device to serve more than one purpose, as in the already mentioned case of the control yoke providing steering commands while the vehicle is moving and turret azimuth and elevation commands when the vehicle is stationary.

Another advantage of software interpretation is quick reconfigurability. If, for example, it was determined that the relationship between the angle of the control yoke and the angle of the vehicle's front wheels should be nonlinear, only a minor programming change would be required to make it so. No rewiring would be required. Quick reconfigurability also implies that other communications systems, payloads, or even vehicles would be easy to accommodate.

The control unit's electronics are based on commercially available boards for the VME bus. A VME chassis and power supply reside below the main CRT driving monitor behind the vertical display panel. The CPU board contains a 10-Mhz Motorola 68010 32-bit microprocessor coupled with a 68881 floating-point coprocessor. Also on the CPU board are 512K bytes of dynamic RAM, 64K bytes of battery backed-up static RAM, 128K bytes of EPROM, four serial ports, and two 16-bit counter/timers. Three additional boards for analog signal input, analog output, and digital I/O complete the hardware.

The CPU is programmed in a compiled version of the Forth language. There is no operating system per se, since Forth provides all the functions that are needed. Since the unit was designed for rugged use in a hostile outdoor environment, there are no disk drives in the system. In lieu of a disk drive, software is loaded into the system by sending Forth source code to the CPU over a serial RS232 link at 9600 baud where a Forth compiler in EPROM compiles it into object code as fast as it is loaded. The compiler places the object code in the static RAM area of the CPU, and the battery back-up maintains it there even if power is removed from the system.

The source code is edited and archived on a Macintosh computer with a hard disk. Debugging requires sending the source code from the Macintosh to the 68010 CPU, testing the compiled code, editing the source as necessary (on the Macintosh), and then resending the portions that were faulty. Once the code is deemed acceptable, the object code (in hex format) is dumped to an EPROM programmer. The static RAM chips on the CPU board are then replaced with the newly-made EPROMS.

SOFTWARE ARCHITECTURE

The main job of the CPU is to mediate between the human operator and the vehicle via the communication system. Most of the CPU time is spent waiting for something to happen. To efficiently accomplish this type of operation with a minimum response time and still be easy to modify and update, an event-driven architecture was chosen. This is illustrated in Figure 7. An "event" is defined as a change of state of the system caused by the actions of the human operator, requests from the communications system, or in some cases by the software internally. The software is said to be "event-driven" because the main routine (the

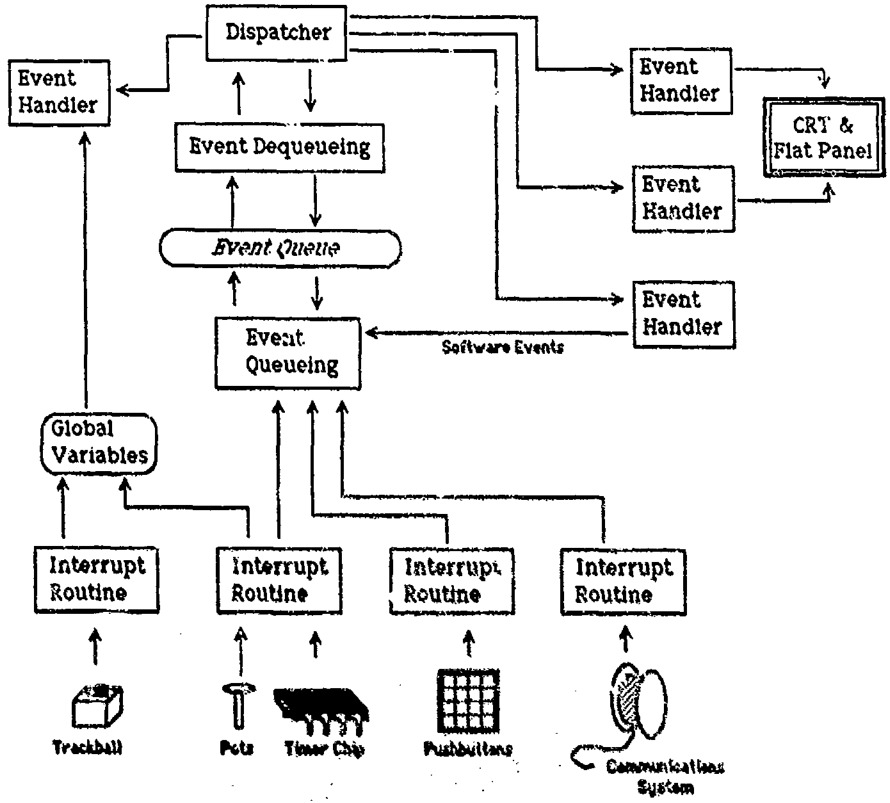

FIGURE 7 - THAP SOFTWARE ARCHITECTURE

"dispatcher") monitors a global data structure called an event queue until a record of an event appears in the queue. It then takes the event record off the queue and passes it to the appropriate "event handler"--a software module that is written to process a particular type of event. When the handler is finished, it returns control to the dispatcher, which resumes watching the event queue until another event appears.

As an example, suppose that the operator pushes a button on the control panel. The buttons are wired through the digital I/O board to generate a processor interrupt when pushed so the processor will be interrupted and will jump to a particular routine for that interrupt. The interrupt routine will determine which button was pushed and will create an event record for the button push. The event record contains information as to what happened (a button push), when it happened, and which particular device caused the event (button number 7, for instance). The routine places the event record into the global event queue and then returns control to the place where the processor was interrupted. The dispatcher notices that there is a new entry in the queue, removes it, notes what kind of event it represents, and dispatches it to the appropriate handler for button pushes. The "button push" handler will then take whatever action is needed for the pushing of button number 7 during the current context, and control will return to the dispatcher.

This software architecture is much more efficient than a polled approach because the CPU is not required to pay attention to a number of dormant inputs; it simply waits for the first device to come to life and then acts on it. In addition, it provides much faster response than polling because there is no need to cycle through all the inputs before discovering that one is active. Best of all, it allows changes to be made in the number of inputs much more easily because only a new handler needs to be written if a new type of event is added. The dispatcher need not be changed at all, and the system does not become slower as new input devices are added.

SUMMARY AND STATUS

A control unit has been designed and fabricated for use with the vehicle and communications system utilized by MICOM in the TMAP project. This control unit is configured to allow extensive upgrading of capabilities through software modification. The initial system allows demonstration of the basic capabilities of vehicle control, simple navigation surveillance, video motion detection, and weapons control. Additional features are being added in an ongoing project at Sandia National Laboratories.

ACKNOWLEDGMENT

The work presented here was supported by the US Army Missile Command (MICOM) through the Teleoperated Mobile All-Purpose Platform (TMAP) Project.

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Robotic Visual Servo Control for Aircraft Ground Refueling

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ABSTRACT

Advances in robotic and sensor technologies open new opportunities for applications of robotic systems. One potential application is the robotic refueling of aircraft. Three basic areas of research are required to accomplish robotic refueling better robotic control, visual servoing and force control. The Air Force Institute of Technololy (AFIT) is conducting initial research into the design and integration of visual servoing. Visual information received from a TV camera mounted to the robot refueler's refueling boom provides the feedback data necessary for employing visual servo control techniques.

The feedback data, the refueling port's centroid and depth, is used to visually guide the robot refueler to the refueling port. To simulate the refueling operation in the laboratory, an artificial, well-defined, high contrast target-background scene is constructed; the target, a white ball, represents the refueling port and a black background represents the surrounding area. The vision-robot system (VRS), composed of a PUMA 560 robot arm and Machine Intelligence Corporation vision system, scans an area until the vision system acquires the target. Once located, the visual servo controller guides the VRS to the target. The integrated VRS uses closed loop, static and dynamic visual servo control techniques to demonstrate the capability of Using a robot equipped with vision for aircraft ground refueling.

The visual servo control techniques were implemented using the PUMA 560's VAL II programming language. Limitations in the VAL II language prevent optimal performance of the VRS, including the following; the inability to perform parallel processing and the inability to determine which robot joints are controlled. However, to date, results successfully demonstrate the VRS's ability to search for a well-defined target in a non-complex environment, and use visual servo control techniques to guide the VRS to the target.

Future research focuses on freeing the VRs from VAL II to provide better control over the robot manipulator. Also interfacing the VRS with AFIT's state-of-the-art Image Processing Laboratory is planned to allow the analysis of more complex target-background scenes found in real world environments. Finally, AFIT is starting research into closing the loop around the robot refueler application by designing better robot position and force control techniques.

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USE OF MOBILE ROBOTS IN RESPONDING TO RADIOLOGICAL AND TOXIC CHEMICAL ACCIDENTS

May 1, 1988

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ABSTRACT

This paper describes the roles and actual operations conducted by mobile robots that were deployed to respond to hazardous situations which developed at the site of several recent accidents/incidents. These robots assumed many of the tasks and missions that are currently conducted by emergency response team members. Specifically this paper will review roles played by mobile robots at scenes of accident/incident sites for the Chernobyl-4 (USSR) nuclear power plant, Goiania (Brazil) Cs-137 contaminated urban area, Washington County (PA-USA) overturned truck, and Prince George's County (MD-USA) overturned truck where radioactive materials or toxic chemicals were released to the atmosphere and the environment. The relative degrees of success and problems experienced by these robots will be identified. Additional missions that the devices could have assumed at the site of these three incidents had the time and the opportunity been available will also be discussed.

1.0 INTRODUCTION

The frequency of incidents associated with the accidental release of radioactive and toxic chemical materials to the environment has become an increasingly serious world-wide problem. These incidents can occur in the nuclear or chemical plant or facility; while radioactive materials or chemicals are being transported by air, boat, rail, or by truck; at the storage/waste dump sites; and within petroleum/gas product pipelines. They can also develop as a result of naturally occurring events such as earthquakes, as exemplified by the release of carbon dioxide from the recent Lake Nios (The Cameroons) incident.

Emergency response team members entering the vicinity of an incident to mitigate its consequences can, unfortunately, become exposed to the released radioactive or toxic chemical materials contaminating the environment. If the radioactive or toxic chemical materials contaminating the environment. If the team members develop adverse synergistic health and/or life-threatening conditions they can become part of the toxic problem. This specific problem can be bypassed and the overall efficiency of the mitigating actions can be improved if many of the activities assigned to the team members within the contaminated zones could be conducted by mobile robots and/or teleoperator/remote controlled vehicles. This paper describes the roles that these devices have conducted at several recent radiological and toxic chemical accidents.

Before delving into reviews of the components of a "mobile robot" and actions completed by these subject vehicles, it is first necessary to describe the devices which are to be discussed in this paper. Presently, there are no universally accepted descriptive terms which define "robots" or "remotely" or "teleoperator" controlled vehicles. The international community has only accepted the definition of a "manipulating industrial robot", or as usually noted, an industrial robot. In view of this vacuum of definitions, informal descriptions of the subject mobile devices are presented below.

A mobile robot is an automatically controlled, multifunctional mechanism which is able to move all or part of itself and is able to maneuver along an unrestricted path. If it is equipped with a manipulator arm, it can complete variable programmed motions for the performance of a variety of tasks and is self-adaptive by interacting with and responding to the environment in which it is operating. On the other hand, the performance of a teleoperator controlled vehicle is remotely controlled by a human operator (i.e., a man-in-the-loop) who at one point in space is able to experience the illusion of being at another (remote) location through the interpretation of sensory data projected back to the operator (telepresence).

The degree of autonomy controlling either/or both locomotion and manipulation functions range from zero to 100 %. Vehicle functions can be completely controlled by the operator, i.e., man-in-the-loop (as in the case for a "teleoperator" or "remote" controlled vehicle), or completely by computer (for a "true" robot). "Telerobotics" resides in the realm between the two limits where responsibility for controlling operations is shared between the two.

Many functions and missions of robots or teleoperator controlled devices have similar requirements and methods of operation. The only difference is whether specific missions may demand human-directed instructions or whether the robot will be able to develop its own task analysis with its on-board package of artificial intelligence (AI) directed autonomous control features. In either case, the two types of devices have similar configuration and performance characteristics and both will, henceforth, be collectively referred to as "mobile robots" in this paper.

Mobile robots and teleoperated vehicles have been available for use in radioactive environments for more than 25 years. It is possible today to deploy off-the-shelf mobile robots in most hazardous situations, which include (but are not limited to) the nuclear, toxic chemical, civilian and military bomb (explosive) ordnance disposal (EOD), mining/tunneling/excavation/construction, security, and firefighting industries. In the case of bomb disposal activities, the robot is a "resident" at the bomb removing agency's storage facility and can be instantaneously deployed to the site of an incident. Most of the newer generation firefighting robots are currently earmarked for the military as resident units on aircraft carriers and at military bases and facilities. Mobile robots are not, however, generally available to respond to global radiological or toxic chemical accidents. The degrees of their availability and subsequent deployment are limited by acquiescence of local emergency response management groups and their willingness to deploy untried systems which have not yet been generally accepted by those responsible management agencies.

2.0 COMPONENTS OF A MOBILE ROBOT

The basic components of a mobile robot consist of eight items. The configuration and geometry (1) of a mobile robot is usually dictated by its primary mission and the location for its employment. The three locomotion techniques (2) being used in most of the current generation of deployed and available off-the-shelf robots are the legged, tracked, and wheeled methodologies. As the legged systems are still basically in a state of development, the latter two systems are the ones most frequently employed in the current generation of deployed mobile robots. The power supply (3) for most systems include batteries, gasoline or diesel engines, hydraulics, or electric (supplied by the "house"). In the latter case, it will be necessary to supply the power through a tether (umbilical cord), thereby restricting the maneuverability and freedom of movement of the robot. The means of communications and control (4) between the operator (or teleoperator) and the robot can be either tethered (cable) or untethered. The most frequently employed non-tethered technology is radio frequency (RF), including microwave. Other tetherless communication technologies are infrared-, laser-, or light-based.

Robotic devices can support many axed manipulative arms which can maneuver light to very heavy loads ranging from 1 kg to more than 220 kg. Other manipulative functions (5) include scraping, bulldozing, transporting sensory packages, vacuuming, spraying, etc. The sensory package (6) for a mobile robot ranges from single vision systems (one video or CCD camera) to multiple cameras to several envrionmental sensing devices. These latter sensors include (but are not limited to) radiation, sound, temperature, humidity detection; analysis of the gaseous or particulate composition of the atmosphere; and placement and detection of x-ray sources. The electronics components (7) for the robots control all maneuvering, manipulative, control, communication, and sensing functions of the vehicle and the operator/vehicle command interface requirements. The integrity of the vehicle can be enhanced if the electronics components are appropriately designed and housed in hermetically sealed packages to protect them from exposure to harsh environments in which they may operate. The degree of intelligence (8) possessed by the mobile robot is dependent upon the level of independent, autonomous activity allowed by the designer, and hence, operator of the robot. This activity is today relatively restricted in that most functions and missions are not standardized and the confidence in having their independent actions remain unguided by human intelligence is "not overwhelming". Autonomous activity is currently being pursued by many researchers and may become a standard item in the next generation of mobile robots.

3.0 LOCATIONS OF DEPLOYMENT AND AVAILABILITY STATUS

Mobile robots have been successfully employed at four recent accident/incident situations. Although only one of the four situations to be described below had a resident robot available for mitigating the consequences of the accident, these devices were brought to the scene of the incident in time periods ranging from 15 minutes to several days after the incident had occurred. One robot was coincidently located near the scene of the incident.

3.1 ACCIDENT NO. 1 - Chernobyl, Ukraine SSR

The accident suffered by the Unit No. 4 of the Chernobyl Atomic Power Station in the Ukraine SSR on April 26, 1986 left many people dead, thousands of square kilometers of contaminated areas, and forced the evacuation of more than 135,000 local residents. The lethal-level radiation levels in the contaminated areas caused extreme difficulties to the rescue workers and other individuals who were given the goal and charged with the responsibility to It was initially estimated that remote controlled vehicles and/or mobile robots were the most appropriate devices that could adequately accomplish this mammoth goal while minimizing the radiation exposure levels of emergency response team personnel and rescue workers. As the Soviet Union did not possess this type of equipment at the time of the accident, they initially pursued outside sources for the robots. The first three robots were furnished by the Federal Republic of Germany's (FRG) Nuclear Emergency Brigade two weeks after the accident. Eventually Finland, Italy, Japan, and Poland supplied remote-controlled devices which complemented those which were developed and produced by the Soviet Union to specifically address the Chernobyl situation(1). The Soviet Union also seriously considered the purchase of six mobile robots to be supplied by two separate manufacturers in the United States(2).

The final inventory of mobile robots and other teleoperator controlled vehicles included the following units: three tracked mobile robots (two tethered and one untethered), a remote controlled 33-ton bulldozer, and five remote controlled and biologically shielded/leaded cab concrete sprayers (the reach of the fully extended five-segmented spraying arm exceeded 60 meters) from the FRG(3); loaders from the Finnish company Toro; an assortment of remotely controlled loaders and bulldozers from Komatsu in Japan; a remote-controlled mining machine from Italy; loaders from Poland; and 11 separate tethered and untethered (radio-controlled) systems specifically designed and produced by the Soviet Union for use at the Chernobyl accident site. Both tracked and wheeled locomotion techniques were employed.

Some of the specific duties conducted by these devices included the following missions: removal of the contaminated material from the roof of the turbine buildings, radiation surveys, visual inspection and surveillance, entombing the remains of the containment building for the destroyed Unit No.4 reactor, cable-laying, pipe cutting (using a welding gas cutting technique), bulldozing relatively "small" roof areas and extremely large outdoor areas, decontamination of vertical and horizontal surfaces, and tool transporter(1). The composite applications and missions for these devices, which collectively produced the largest and most intensive use of mobile robotic devices ever assembled in one concentrated area, saved the health, and most likely the lives,

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(1) Adamov, E. O. (USSR Kurchatov Institute for Atomic Power), Personal Communications and unpublished presentation at American Nuclear Society Sponsored International Symposium on Remote Systems and Robotics in Harsh Environments, Pasco, WA (USA), March 29 - April 2, 1987.
(2) Worthington, R., Chicago Tribune, May 19, 1986, p. 6.
(3) Meieran, H. B. (PHD Technologies Inc.), unpublished presentation at American International Symposium on Remote Systems and Robotics in Harsh Environments, Pasco, WA (USA), March 29 - April 2, 1987.

of many of the thousands of workers who were brought into the site to mitigate the consequences of the accident.

3.2 ACCIDENT NO. 2 - Goiania, Goias, Brazil

In September 1987, an abandoned contained 1375 Ci Cs-137 radiation source was found in an abandoned building by some of the local population in the city of Goiania, Goias, Brazil(4). As the finders of the Cs-137 container considered it to be a source of scrap metal, they brought the container to a scrap dealer. The Cs-137 chloride powder was distributed around the facilities after the container was successfully opened. Eventually the released powder contaminated scores of people and a part of the city of several hundred thousand. This contamination problem was not brought to the attention of responsible authorities until September 29 when the first of many people were diagnosed to have symptoms of Acute Radiation Sickness (ARS). At least four people have died from overexposure and scores more are still confined to hospitals or are under medical surveillance by the health authorities.

Although Brazil received offers of assistance of remote-controlled decontamination technologies from other countries (the Peoples Republic of China, Federal Republic of Germany, France, Italy, the Soviet Union, and the United States), they elected to proceed independently with this activity using indigenous, off-the-shelf mobile teleoperator controlled vehicles(5). These vehicles consisted of a four-wheeled mobile robot that possessed a manipulator arm and two video cameras and a loader/bulldozer that was modified to be remotely controlled.

The mobile robot was developed several years ago by a Sao Paulo company, Blump Digitone Ltda. This vehicle was "drafted " and immediately deployed in Goiania in late October and equipped with a radiation survey meter. All command signals and visual data were transferred back to the teleoperator via RF links. As the arm for this robot was not capable of lifting loads in excess of 5 kgs, its manipulative functions were limited to lifting relatively lightweight loads. Although this vehicle possessed limited manipulative and sensory capabilities and was not designed to operate in a radioactively con-

(4) Alves, R. A. (President of Brazilian Nuclear Energy Commission), "Preliminary Report on the Radiological Accident in Goiania", Presentation at Latin American Section of American Nuclear Society sponsored Conference on Public Acceptance of Nuclear Energy, Rio de Janeiro, Brazil, March 14-15, 1988.

(5) da Silva, C. B. (President of Blump Digitone, Sao Paulo, Brazil), Personal Communications.

taminated environment, it was, nevertheless, still able to conduct radiation and visual surveys and was able to lift and transport small quantities of contaminated material.

The other device was a Massey-Furgeson loader/dozer that was backfitted to be remotely controlled by a teleoperator located more than 2 km from the contaminated area (if the need arose to place the operator at this distance). Its mission was to plow up to 1 meter of contaminated soil and lift it to a truck. Initial reports from the site indicated that the success in operating this device was limited.

3.3 ACCIDENT NO. 3 - Interchange at Interstate Highways I-70 and I-79, Washington County, PA, USA

An MPR-800 mobile robot was used on November 14, 1987 to respond to an accident involving a tractor-trailer chemical tanker carrying a toxic acid. The tractor-trailer overturned while attempting to enter Interstate highway I-70 from a steep grade on I-79 in Washington County, PA, about 48 km (30 miles) south of Pittsburgh. The roadway was covered with diesel fuel and acid which had leaked from the tanker.

A demonstration of the mobile robot for the Washington County Emergency Services group of HAZMAT and firefighting personnel at a local fire station had just begun when the fire alarm sounded. As all personnel at the demonstration had to respond to the alarm, which turned out to be for the overturned tractor-trailer, it was requested that the robot be transported to the site of the accident and be made available for service. As soon as the robot arrived at the scene of the accident 15 minutes after the first alarm had been sounded, it was pressed into duty. A fire hose was attached to its manipulating arm and the robot proceeded to washdown the roadway surface onto which the diesel fuel and acid had spilled. The robot remained at the scene of the accident to provide visual surveillance support of site activities and to lend assistance to the HAZMAT crew in the event that additional acid would leak from the tank or if a fire could have erupted during attempts to upright the overturned vehicle.

The 6-wheeled, 800 kg MPR-800 mobile robot, manufactured by the OAO Corporation of Greenbelt, MD, possess a remote-controlled manipulator which can pick up loads in excess of 110 kg when the arm is fully extended to 2.5 m. Furthermore, the robot can pick up loads in excess of 220 kg when the manipulating arm is not fully extended. The vehicle also possesses two video cameras and the whole system communicates with the operator by radio; there are no cables present.

3.4 ACCIDENT NO.4 - Interstate Highway I-95, Prince George's County, MD, USA

An RMI mobile robot was used on March 28, 1988 to respond to an accident involving a truck carrying a load of dry-cleaning chemicals which had overturned when it veered off south-bound Interstate highway I-95[6]. The accident occurred in Calverton, Prince George's County, MD, just north of the Washington, DC I-495 Beltway, after having blown a tire. The accident caused a considerable upheaval in the traffic flow on this major highway, as well as a forced evacuation of several hundred local residents from their homes, because there was an imminent threat of a spontaneous ingnition of the chemicals and the possible formation of oxalic acid and chlorine.

The RMI mobile robot was attached as an EOD device to the Prince George's County police. It was used to survey the accident site and transmit video images (listing of the contents of the containers, locations of specific sources of leaks) back to the teleoperator. The 6-wheeled, 105 kg RMI mobile robot, which was manufactured by Pedsco-Canada Ltd, of Scarborough, Ontario, Canada, possesses a remote-controlled manipulator which can pick up loads in excess of 30 kgs and a remote controlled camera. Additional manipulative missions were not assigned to this robot at this time as it was not capable of lifting the heavy spilled containers (which weighed in excess of 100 kg).

4.0 LESSONS LEARNED

4.1 SUCCESSES

The versatile capabilities of many robots enables them to respond to situations other than that for which they were originally designed. Many of the robots and remote-controlled devices employed at the site of the Chernobyl accident were designed for bomb disposal, earth excavation, surface grading, and construction missions. Both the MPR-800 and RMI mobile robots had been designed to operate as explosive ordnance devices. Their utilization as assistive devices for toxic chemical accidents was successfully demonstrated.

The Blump robot was designed to operate as an educational tool was also infrequently utilized as a show robot. It was, nevertheless, employed in a highly radioactively contaminated area and successfully completed its assigned missions.

Despite the list of operational problems encountered by the robots at Chernobyl presented below, many of them continued to perform under most adverse radiological and geographical conditions.

(6) Lancaster, J. and Riley, R., "Danger Hard to Assess When Chemicals Spill", Washington Post, March 30, 1988, p. B-1 -B-2.

4.2 OPERATIONAL AND PERFORMANCE PROBLEMS

The Soviets encountered several operational and performance problems while using numerous remote controlled vehicles at the site of the Chernobyl accident. Most of the problems were associated with the following robot components: video and vision systems, power supply, tether, communications and control, electronics, lack of radiation hardening, modularization, mobility, and decontamination.

The Soviets had considerable difficulty maneuvering their vehicles over the maize of tethers; these cables limited the mobility of the devices and in some cases were severed by the tracks of the vehicle, thus forcing the robot to cease functioning. The lack of wide-angle lenses and limited use of pan-and-tilt mechanisms for the video cameras limited the degree of telepresence of the operator at the scene of operation. Furthermore, teleoperators were not able to see what they were doing after the intense radiation levels had caused lenses of video cameras to become opaque. These visual limitations forced the Soviet personnel to operate the vehicles using line-of-sight principles, thereby placing them much closer to higher radiation levels than they had originally intended to be. Tracks and wheels of the vehicles could not negotiate over much of the obstacle-cluttered environment and also became bogged down in the semi-liquid melted roof-top bitumen (located on the top of the turbine buildings). The reliability and availability of the mechanical parts and the control systems were also affected by the high (600-800 r/hr) radiation fields; they frequently failed.

In order to continue using restored disabled robots, it was necessary to first retrieve them from their stalled position and replace non-functioning components with suitable replacements. As most of the components on all of the vehicles were not designed to be rapidly and easily replaced, a considerable amount of time was lost in replacing these nonfunctioning components. The Soviet scientists were emphatic about incorporating modular, easy to replace radiation-hardened components into their next generation of mobile robots. Other significant design and performance features that the Soviets are considering for their wish list of items to be included for future robots are the use of radio-controlled rather than cable communication techniques and easily decontaminatable physical configurations.

The operational and performance problems encountered at the Goiania accident have not yet been quantified and none were noted during the Washington and Prince George's Counties accidents.

4.3 ADVANCED PLANNING

Although some problems regarding the use of mobile robots responding to emergency situations have arisen, these devices have demonstrated their capabilities and versatilities in life-threatening situations. Their contributions in response to accidents can be effectively enhanced through more advanced planning and strategic placement of devices in the hands of operators of emergency response systems prior to the time of an emergency. Specific examples of the use of mobile robots in these situations were previously presented by Meieran(7).

The operators of the MPR-800 robot, which was originally designed to remove unexploded ordnance, who were present at the Washington County toxic chemical accident site claim that the robot can operate for an unlimited time in temperatures of up to 60 degrees Celsius and for short times in temperatures in excess of 200 degrees. This enables the robot to be u ed for fighting fires and operating in extremely high temperatures in situations for which the robot was not originally designed.

4.4 TRAINING

Other than the Washington and Prince George's Counties incidents, there were no trained operators of robotic equipment available at the site and the time of the accidents. Valuable time was lost during the initial stages of the accidents to train emergency response team personnel to operate and maintain the vehicles; this time could have been more appropriately directed towards the efforts to mitigate the consequences of the accidents which in turn could have limited the extent of contaminating personnel and damage to the environment.

The Soviet scientists reported that they did not have sufficient time to prepare for the activities for the robots and train their teleoperators. On-the-fly determinations of the specific missions and operational scenarios caused some confusion and limited the efficiency of their performance.

4.5 RECOMMENDATIONS

The considerable size of the Soviet developed data base on the operation and performance of multiple units should be reviewed for its description of missions to be conducted at the sites of future toxic incidents.

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(7) Meieran, H. B., "Mobile Robot Response to Actions Associated with the Release of Hazardous Materials", in Proc. American Nuclear Society Sponsored Topical Meeting on Radiological Hazards - Perspectives and Emergency Planning, Bethesda, MD, September 15-17, 1986.

With respect to toxic chemical accidents, other missions envisioned for mobile robots to be conducted at the scene of the accident include general visual surveillance, monitoring the atmosphere and surfaces for toxic chemical contaminants, decontamination of contaminated surfaces, fighting fires with water or chemical sprays, off-loading barrels and drums, turning valves on/off, transporting tools, using hand tools, connecting/ disconnecting hoses, inspection of vehicles and structures to assess their integrity, and digging drainage ditches.

5.0 CONCLUSIONS

The use of mobile robots and teleoperator controlled vehicles at several recent accidents has demonstrated their successes and identified some of their design and operational problems. Missions conducted by these robots included the following functions: manipulation of material, surveillance/inspection of the general area, removing contaminated surface material, dismantling contaminated structures, decontamination, construction of shielded facilities, and removal of contaminated materials from the vicinity of the incidents. Some of the more significant performance problems that must be resolved in order to enhance the respectability and availability of these systems include: design and functional considerations, modularization of critical components, improved performance factors, improved training, and mission assignment priorities. Acquisition, availability, and training procedures must be established along with policies to implement the coordination of utilization and sharing of available resources.

The capabilities of mobile robots responding to radiological and toxic chemical accidents have been successfully demonstrated and the frequency of their use in this capacity is expected to dramatically increase in the near future. Their immediate deployment at the scene of an accident can significantly decrease the incidence of injuries and contamination to personnel and destruction of property.

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THE VERSATOOL III

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Introduction

In the past, engineers and scientists have struggled over the concepts of end effector design. End effectors can be classified into one of three categories;

1. Universal Type
2. Tool Changer System
3. Custom Tooling - Task Oriented

Each classification has distinct advantages which align with task objectives.

Universal type end effectors (Figure 1) are capable of performing a variety of tasks. With adjustable gripping patterns, they can match the shape of many objects. The universal end effector is well suited for handling various materials but it is not task-oriented tooling.

The tool changer systems uses a variety of tools to accomplish tasks. Typically this end effector system would have a torque transmission shaft inside the arm which would accommodate specific tool operation. Tool changers tend to get large and mass increases as the library of tools grows. This library, incidentally, should contain a universal end effector for handling and releasing parts.

Special tooling is extremely task oriented and its capabilities are limited to a finite range. Equipping a Space Station robot with a single task oriented end effector would be worthless. Designing several pieces of tooling would require a tool changing mechanism and the mass and size advantages would vanish.

The optimum Space Station end effector is an integration of the universal and tool changer categories. In addition, size and end-of-arm mass will be reduced by allowing the robot to function as its own tool changer.

A universal and programmable tool changing end effector, the VERSATOOL III™, was designed to accomplish this. Using the universal end effector as the tool changer also reduces the size and mass of the tool library.

Immediate needs exist in the Space Station Program, nuclear fuel and chemical industries. The VERSATOOL III program was initiated to develop this advanced end effector system. In addition, some classic end effector problems are solved by the VERSATOOL III system.

Previous Work

Quite a bit of work has been done in the field of end effectors. Most of this work falls in the categories of either prosthetics or special tooling. Some work is being done by companies like Robo-Tech Systems on universal end effector systems.

It was announced that a computer-controlled electric hand was matched with the Utah arm (1). The hand has a small motor located in the palm and gear systems which drive the fingers closed. Power of the grip is adjusted automatically by a clever two-speed gear train engages, switching the hand into lower gear that can exert up to 22 pounds of force. Though the hand weighs less than one pound, Utah researchers are developing a lighter model.

Salisbury and Craig designed a mechanical hand (2) with nine degrees of freedom using three articulated fingers. Each finger has a revolute joint that is substantially perpendicular to the curl plane of that finger. Articulation is induced by teflon coated tension cables. Motors are located in the wrist of the hand. Each tension cable has a strain gage attached to a critical idler pulley in a manner that allows indirect measurement of the tension in the cable at any given time. Often called the Stanford-JPL hand, this mechanism is quite similar to the hand developed by Okada in 1977 (3).

Jacobsen, et al. have developed the "Utah/M.I.T. Dextrous Hand" (4). This a tendon driven multiple prehension hand with multichannel touch sensing capability. Although the design of this hand is prosthetic in nature, they are exploring some of the traditional robotic challenges. Specifically, should one exchange hands to obtain new tooling or should the multiple prehension hand be used. Their opinions tend to follow Robo-Tech's, "At that point, it is probably more desirable to provide additional functions to individual grippers to reduce their overall number..." (4).

Industrial robotics applications have brought on a tremendous demand for end effectors. The manufacturing engineer is encouraged by the robots capability to perform multiple tasks. This reduces his capital equipment investment. However, as he searches for the tooling or end effectors to perform multiple tasks, he is confronted with the cycle time problem. Industrial robots are relatively slow for manufacturing applications. It takes a robot 2 to 3 times as longer to add a part in automatic assembly than conventional systems. The trend in industry is towards special purpose tooling except for unusual applications.

The criteria for a Space Station robot end effector are somewhat different than those found in industry. Reliability, versatility and capability are more important than the initial product. Cost, cycle time and payback are secondary to overall performance. This prompted Robo-Tech Systems to develop the VERSATOOL III System for IVA and EVA robotics.

Basic Program Technology

It is generally acknowledged that the EVA robot will require end effectors that utilize interchangeable tooling to perform specific tasks in space station assembly. Tooling with broad capabilities will increase the versatility of the EVA robot and decrease system mass and tool changing. A "universal end effector" must be considered.

Robo-Tech Systems has invented an end effector system for solving these problems. The system is a universal type end effector which has tool changer interlocks. Figure 2 shows this end effector opend to grip tooling. The end effector can, therefore, function as a multiple prehension end effector for gripping, moving and orienting objects. However, when special tasks demand unique tooling, the end effector grips and interlocks with that tooling to perform a unique task (Welders, SHCS Driver, pliers, et. al.).

Power and control inputs are have traditionally been provided by a mechanical linkage between the arm and the end effector. However, feedback from electronic sensors cannot be transmitted through a mechanical coupling. Recently, Clark has invented a self-aligning electric coupler which allows the attachment of the electrical tooling to the robot arm (U.S. Patent 4,545,723).

The Advantages of Interchangeable Tooling

Changing hands is a method of increasing robot versatility. The hand is separated from the robot wrist, and a new hand is inserted. This process can be completed within a few seconds. When the entire hand is interchanged, new tooling or a new finger bending mechanism is made available to the robot. This concept has advantages because it allows the robot system to handle objects of significantly different shapes, or to change tooling and perform a manufacturing function other than material handling.

Changing hands will require some cycle time since the arm must move to a new location, deposit the hand, move to the new hand, acquire it and return to the work station.

To reduce the lost cycle time that occurs while the robot is changing hands some manufacturers have proposed a "multiple hand system", where the robot has several gripping devices attached to its wrist at the same time. By rotating its wrist, or through some other independent motion, the robot can move a new hand to a desired position at the work station. Very little, if any, cycle time is lost with this concept. The primary disadvantage of a multiple hand system is that each hand is carried all of the time at the distal point on the robot arm. This increases the mass at the end of the robot arm, the most detrimental point considering both robot dynamics and positioning accuracy. Increasing mass at the end of the robot arm directly reduces payload capability. Robot specialists general concur to keep the mass at the end of the robot arm to a minimum value. Therefore the VERSATOOL III System will keep the tooling mass attached to the robot frame to reduce torque and rotation during the work cycle.

The Clark Coupler

A very important breakthrough in electrical coupling was recently patented by NASA, Marshall Space Flight Center. The inventors, Keith Clark, et. al., have discovered a coupler that allows the male and female segments to self-align during the coupling process. The VERSATOOL III end effector will use an improved version of the Clark Coupler.

The Clark Coupler is made up of a series of contact rings, stacked axially in a conical design. The number of rings determines the number of contact elements.

No limiting value has been established for the number of contact elements in a Clark Coupler. It is felt that the number of contact elements is a function of the size of the coupler. We estimate that 6 to 8 contact elements can be established in a coupler that would easily fit into the VERSATOOL III palm. However, it is possible to use 2 or more couplers to significantly increase the number of control elements if necessary (Figure 3).

Space applications are ideal for the Clark Coupler. The absence of oxygen, moisture, et. al., allow the conducting surfaces of the connector to transmit power voltages and control inputs perfectly.

Catastrophic failure, however, is possible due to micrometeorites. To prevent this problem, Robo-Tech Systems has designed a shielding mechanism which will cover the coupler mechanism when it is not engaged.

The original Clark Coupler would self-align about the X and Y axes and was symmetrical about the Z axis. Our application studies have indicated that the coupler must be capable of accommodating alignment rotation about the Z axis. The improved Clark Coupler has modified contact elements which will allow Z axis rotation. These elements also eliminate the risk of entanglement during the coupling and decoupling process.

The revised Clark Coupler allows the Versatool end effector to easily acquire tooling and establish control and power voltage and current.

Tool Gripping and Locking

An effective tool changer mechanism must have a gripping and self-locking mechanism that will hold the tools at all times after they have been attached. It is not reasonable to expect that an electric drive motor would remain in a stalled state, utilizing current to hold the tool. Therefore the drive motor must act only as a latching mechanism to either open or close the tool locking mechanism.

Tools must be firmly locked about all 6 degrees of freedom. Robo-Tech Systems has designed a coupler mechanism that will achieve these requirements. The coupler mechanism uses a VERSAGRIP III end effector. The fingers close about the tooling constraining motion in the X and Y directions and constraining rotation about the X & Y axes. Tooling is locked into position along the Z axis by small clamps attached to the main fingers (Figure 4). Additionally, these appendages prevent the tooling from rotating about the Z axis when it is gripped in the end effector.

Self-locking of the fingers about the tooling is accomplished by the ball screw transmission drive and finger opening-closing mechanism. The ball screw has a unique positive latch which locks the fingers whenever motor current is withdrawn.

Tool Release

Regular release of tooling is accomplished by opening the end effector at the tool station and closing the end effector around the base of the new tool to be acquired. To avoid accidental release of tooling during working operations, a proximity sensor is located on the end effector to verify that the arm is correctly positioned against the tool changer.

An emergency condition may arise which would require the availability of a universal type end effector. However, the VERSAGRIP III may be engaged with another piece of tooling. Under these conditions, the end effector could be opened immediately, discharging the tooling, and leaving a universal gripper for immediate use. In EVA robotics, a tooling constraint or recover procedure would be implemented.

The Versatool Box

Almost any type of tool can be adapted to the VERSATOOL III end effector. Therefore, much of the Space Station robotics challenge will be to accurately determine what tools are necessary and design them. Clever engineering will take advantage of redundancy and standardization to reduce the number of tools to a minimum practical number. This is a basic description of how some of these tools might be designed.

The Socket Head Cap Screw Driver Tool

All blind fasteners with "heads" should be of a design similar to the Socket Head Cap Screw. A minimum number of socket sizes should be established.

The Socket Head Cap Screw Driver would consist of a tool base for location within the Versagrip hand and an electrically driven hexagonal shaft. The hexagonal shaft would telescope allowing smaller elements to retract until the correct size drops into the Socket Head Cap Screw (Figure 5). Torque could be sensed by a transducer located on the tooling.

This tool could handle a large percentage of the "temporary" fastener requirements. The remaining hexagonal fastener requirements would be handled by an adjustable nut driver tool mechanism.

The Adjustable Nut Driver Tool Mechanism

This tooling consists of a base which attaches to the end effector, an electrically driven torqueing mechanism and a series of single axis, telescoping hexagonal drivers (Figure 6).

Applying a force along the Z axis, between the tooling and the fastener, will cause the fastener to push the small sized hexagonal elements down until it nests properly within the correctly sized tool. Torque can then be applied to tighten or remove the fastener. Similarly, new fasteners may be applied by acquiring them from a dispensing element.

Dispensing Tools

It may be desirable to dispense high viscosity fluids such as lubricants and sealants. These materials could be dispensed in a universal tool which would handle one or more sealed cartridges. We are currently pursuing a dispenser which utilizes small standard sized plastic tubes. The dispenser has a cutting mechanism to open the tube. It can cut the tip at many positions along its conical sides and at one of several angles, producing desirable flow rates and patterns. Material is forced out of the tube by two rollers which progress from the back to the front.

The design of the tube is different from a traditional "toothpaste" tube. The toothpaste tube is primarily cylindrical. The tube dispensing mechanism developed at Robo-Tech Systems utilizes a conical tube where the back end has been closed and sealed. This allows for virtually 100% recovery of the materials present in the dispensing tube.

Processed tubes are then ejected into a waste container and a new tube is automatically inserted. Three motors are required to operate the tube dispensing mechanism along with various transducers.

An Impact Mechanism

An Impact Mechanism (hammering device) would be useful on occasions to overcome friction locking and other mechanical interference conditions. In all hammering operations the force exerted on the target is reflected back into the arm of the robot. It is not desirable to have a great amount of force applied to the robot arm. However, to generate impact, a mass must be accelerated from zero relative velocity and decelerated.

The impact mechanism designed at Robo-Tech Systems (Figure 7) is based on two key principals. First, the force transmitted to the robot arm must be nearly, if not equal to, zero lbf. Second, impact is achieved by accelerating a low mass "hammer" to a high velocity. That force is balanced against a higher mass object which will be accelerated to a lower velocity.

The hammer has a small bullet type projectile which is driven forward by springs within an encasement until it extends and strikes the target. The encasement (the high mass object) reflects the force exerted by the acceleration of the hammer. However, because its mass is higher, it does not move as fast or as far in the opposite direction. Momentum of the hammer mechanism is absorbed by a "shock absorber" before it is reflected onto the robot arm.

An electric motor, located in the tooling base, drives a retracting mechanism which withdraws the projectile back into the casing and compresses the springs. Rotation in the opposite direction causes the mechanism to release the projectile and fire the hammer a second time.

Sawing Devices

Two Sawing Devices have been designed for the end effector. The first uses a simple rotary "drill-type" saw. Two sets of teeth are located on the saw. The first set is parallel to the cylindrical side wall. The second set of teeth extends 90 degrees out from the cylinders surface wall (Figure 8). Although this tool is quite useful for most cutting operations, it is conceivable that a situation would exist where a large cut might have to be made along a straight line. Perhaps this cut might even have to be made from a "blind" condition.

The second saw design uses a reciprocating blade which extends out approximately 4 inches from the face of the tooling (Figure 9). This blade is electrically driven and reciprocation is generated by a crank shaft linkage mechanism.

Other Tools

Other tools, welders, soldering devices, etc. can be designed into the VERSATOOL III System. For many of the gripping and clamping applications, the end effector will do the task. It is desirable that the number of tools be kept to a minimum in order to keep the system practical. A study of parts should be initiated to determine what tools are necessary to add and remove parts. Additionally, engineers should be employed to design tools for servicing the Space Station elements.

Down, Around and Under

During a recent discussion with Dr. Byron Purves, Boeing International, he stated that "The primary challenge for the end effector will be in getting down, around, and under objects to perfo critical tasks." We reacted favorably to this challenge at Robo-Tech Systems. The VERSATOOL III System contains a design for tooling that will allow the robot arm to reach into unusual places. For example, gaining excess to electrical components through a 1/2 inch diameter hole or reaching under a 1/2 inch slot and bending back and up towards the front panel.

The tooling will clamp into the Versagrip III end effector in the traditional manner it uses a small "elephant trunk" finger, approximately 24 inches long, to reach around corners and into unusual places. The finger mechanism is a series of parallel plates connected by tendons which are powered by electric motors in the tool base. Motor operation causes specific tendons to extend or retract, resulting in curling at specific positions along the finger itself.

An additional end effector is attached at the end of the finger. We anticipate this will be a small 3-jaw chuck type gripper because of its compact size and high versatility.

Computer simulations of the finger mechanism show that it is capable of bending completely around through 180 degrees if necessary. We expect that this end effector will solve many of the "service to inaccessible locations" problems which currently have engineers concerned. This tooling breakthrough presents a strong argument for the use of robotics in space. The VERSATOOL III System is now able to gain access to areas that an astronaut would have difficulty servicing.

Future Plans

Although the design for a VERSATOOL III System has been completed, a complete system has not been built. This is the next major phase of the program. Additionally, it is important to perform a study of Space Station parts to begin the design of the tooling necessary for fabrication and servicing.

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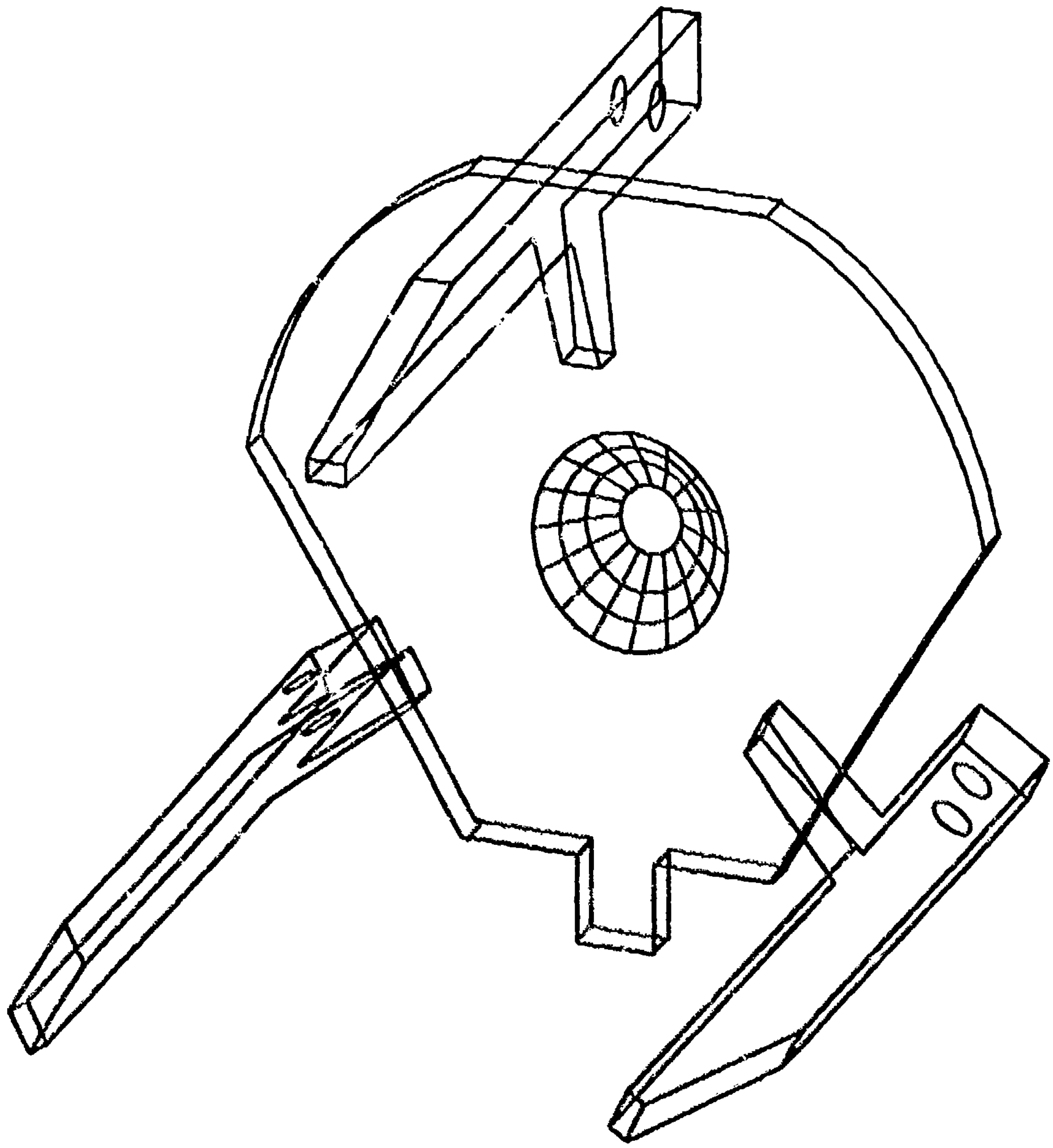


FIGURE 1 - A UNIVERSAL END EFFECTOR

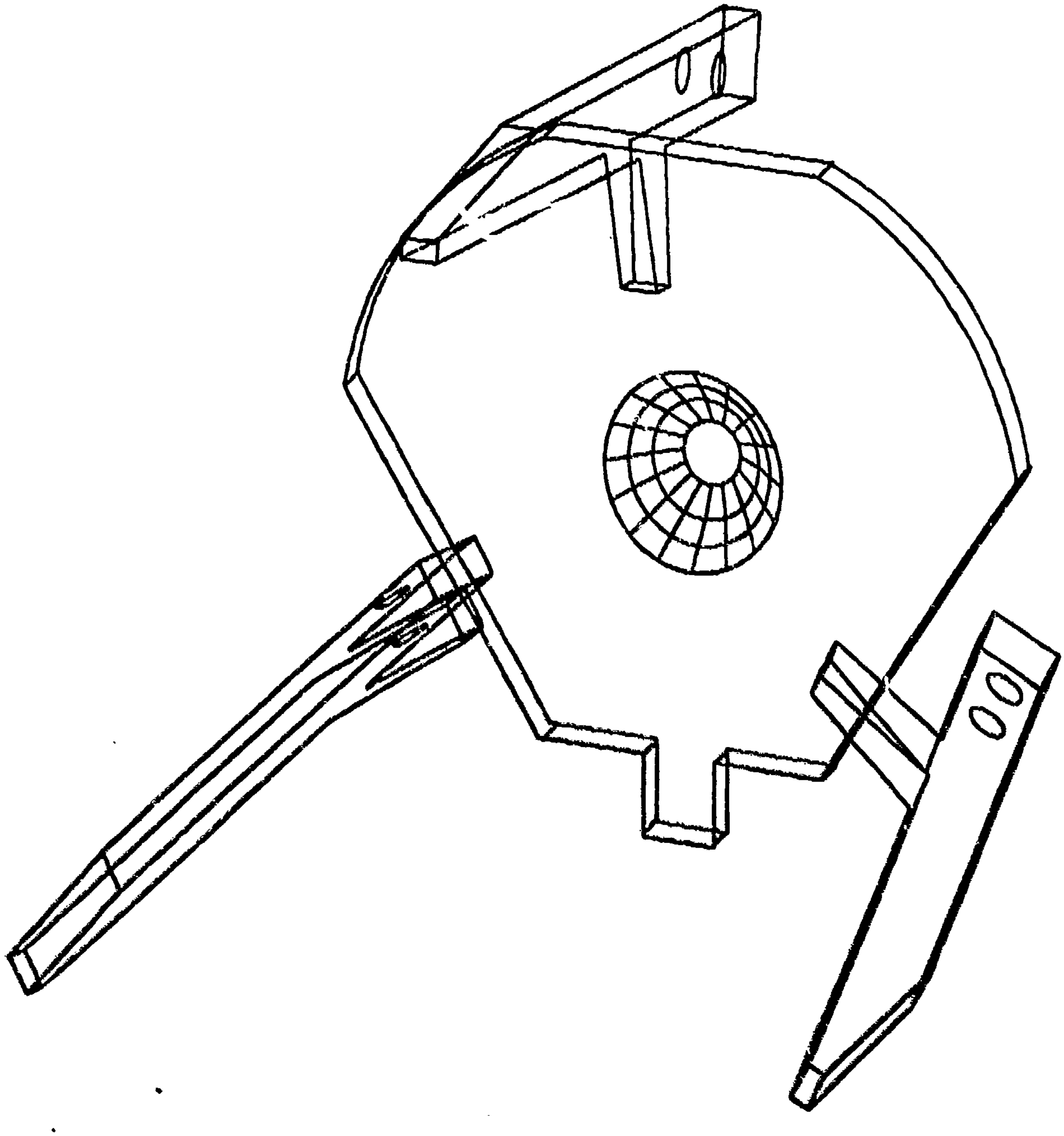


FIGURE 2 - THE VERSATOOL END EFFECTOR

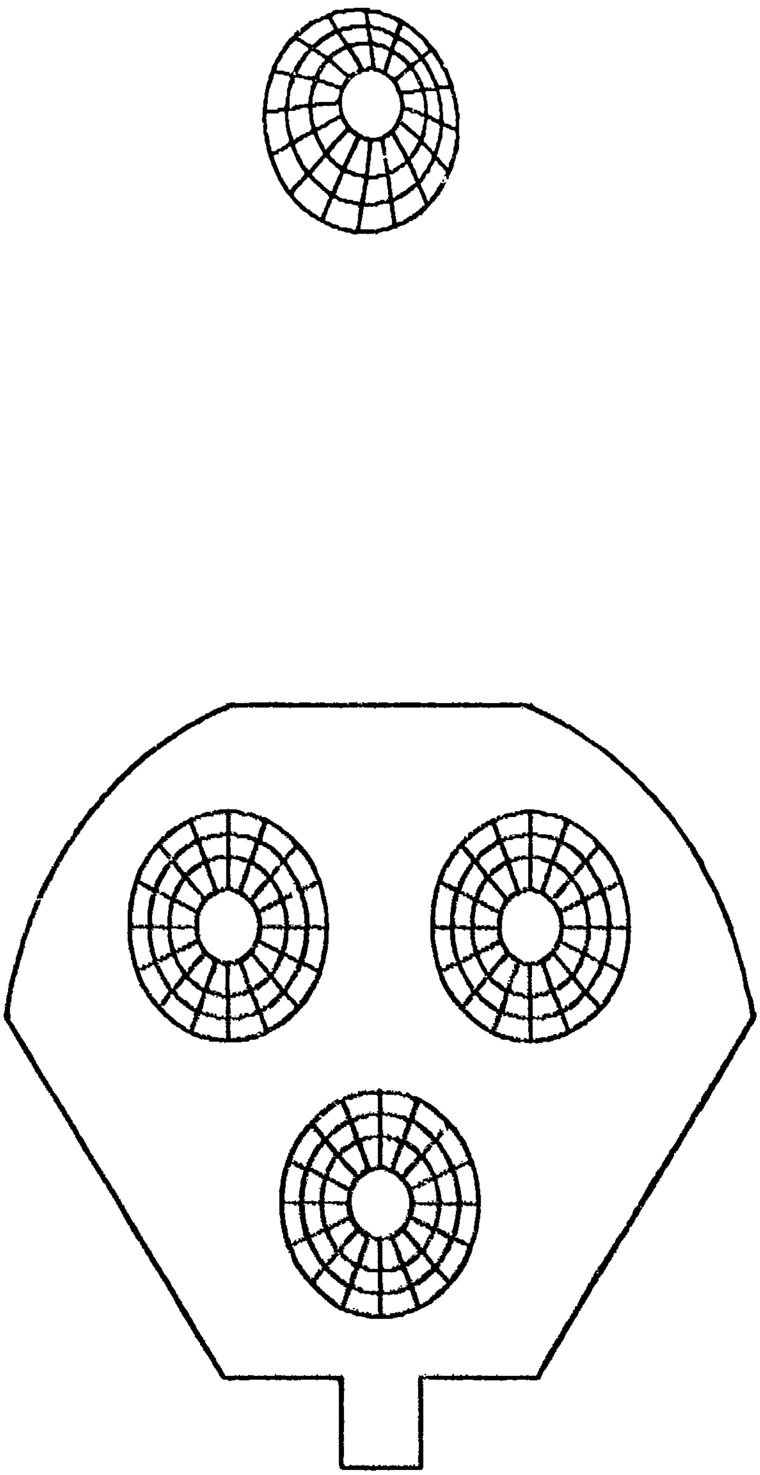


FIGURE 3 - THE CLARK COUPLER

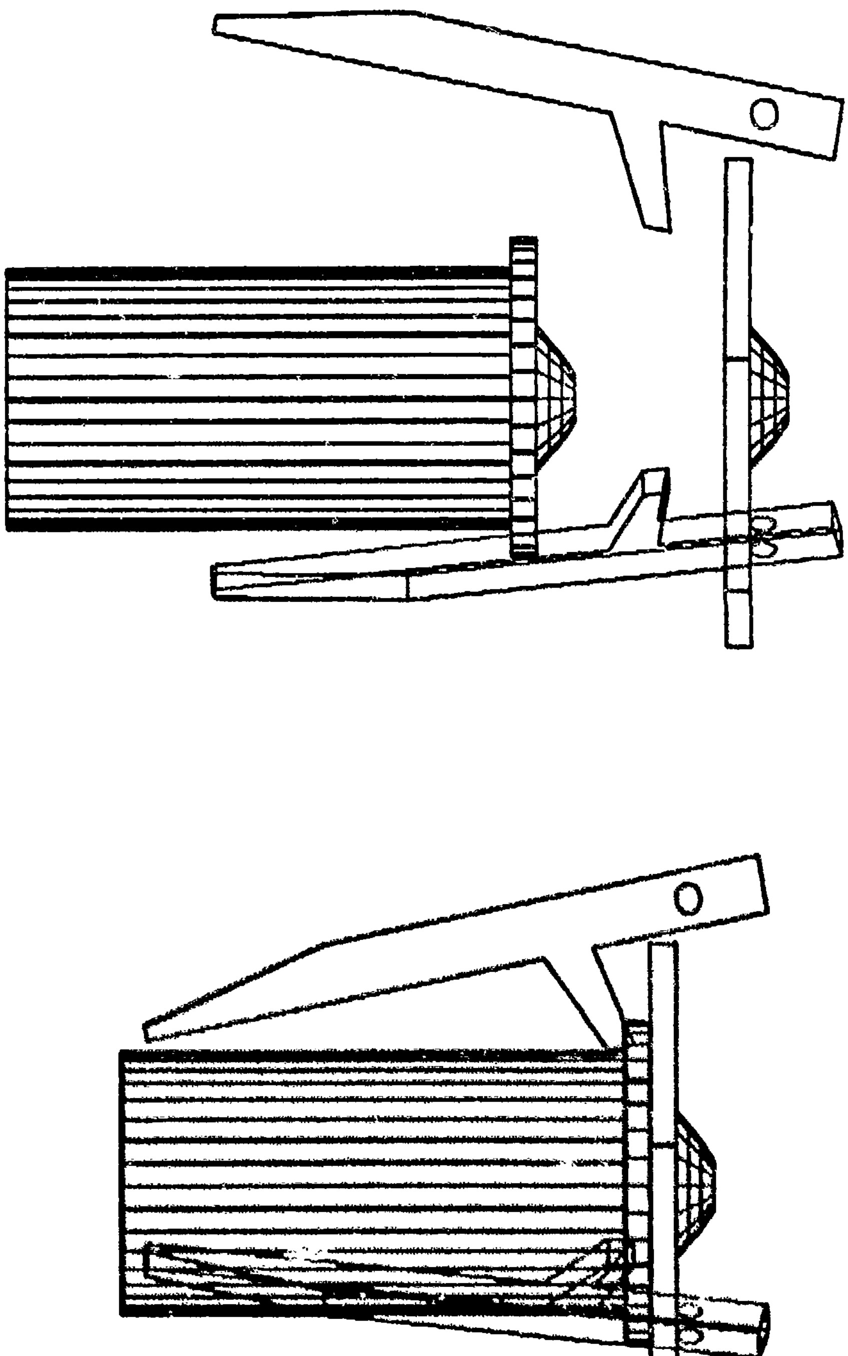


FIGURE 4 - THE TOOL LOCKING PROCEEDURE

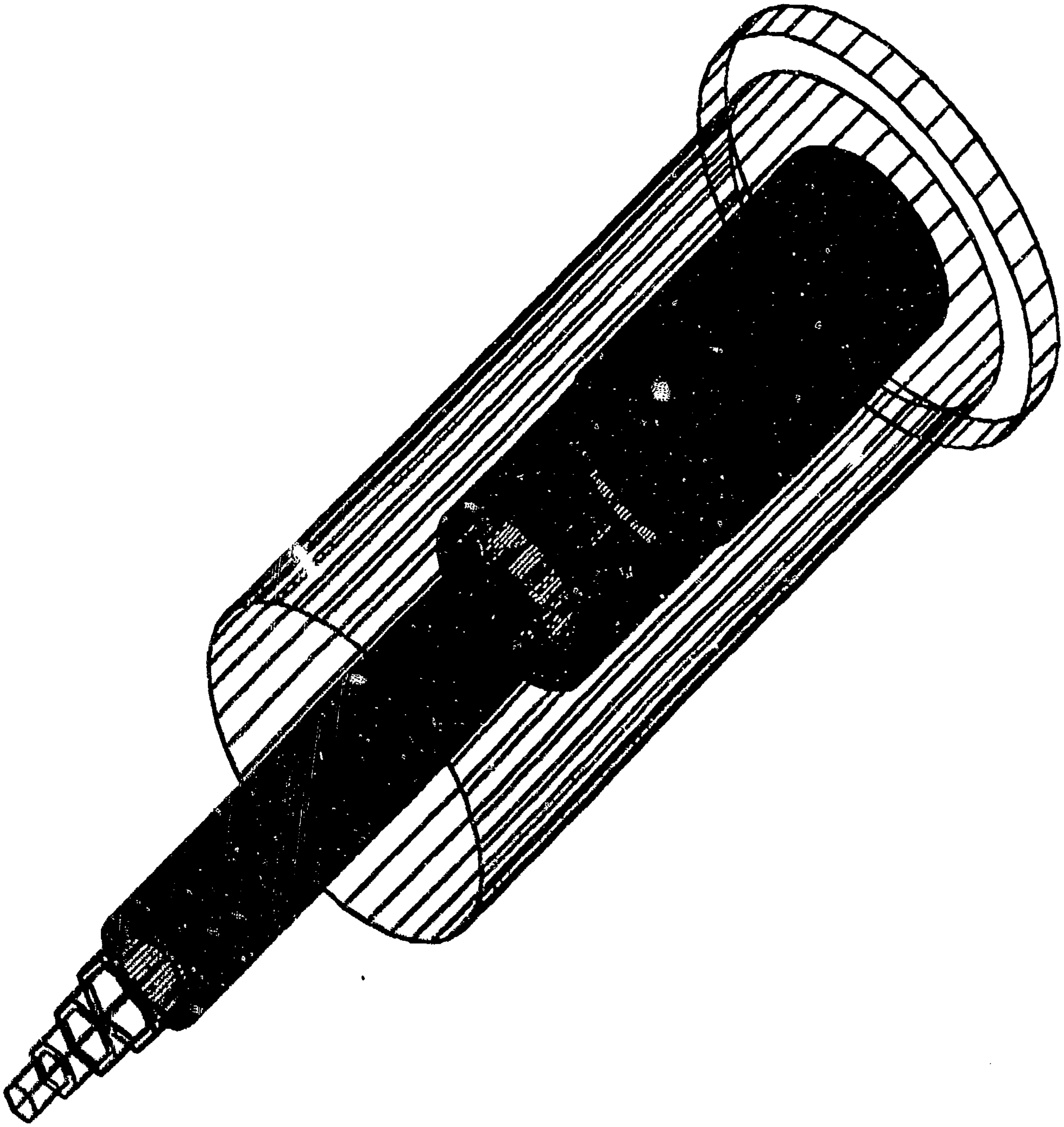


FIGURE 5 - TOOLING FOR SOCKET HEAD CAP SC^^WS

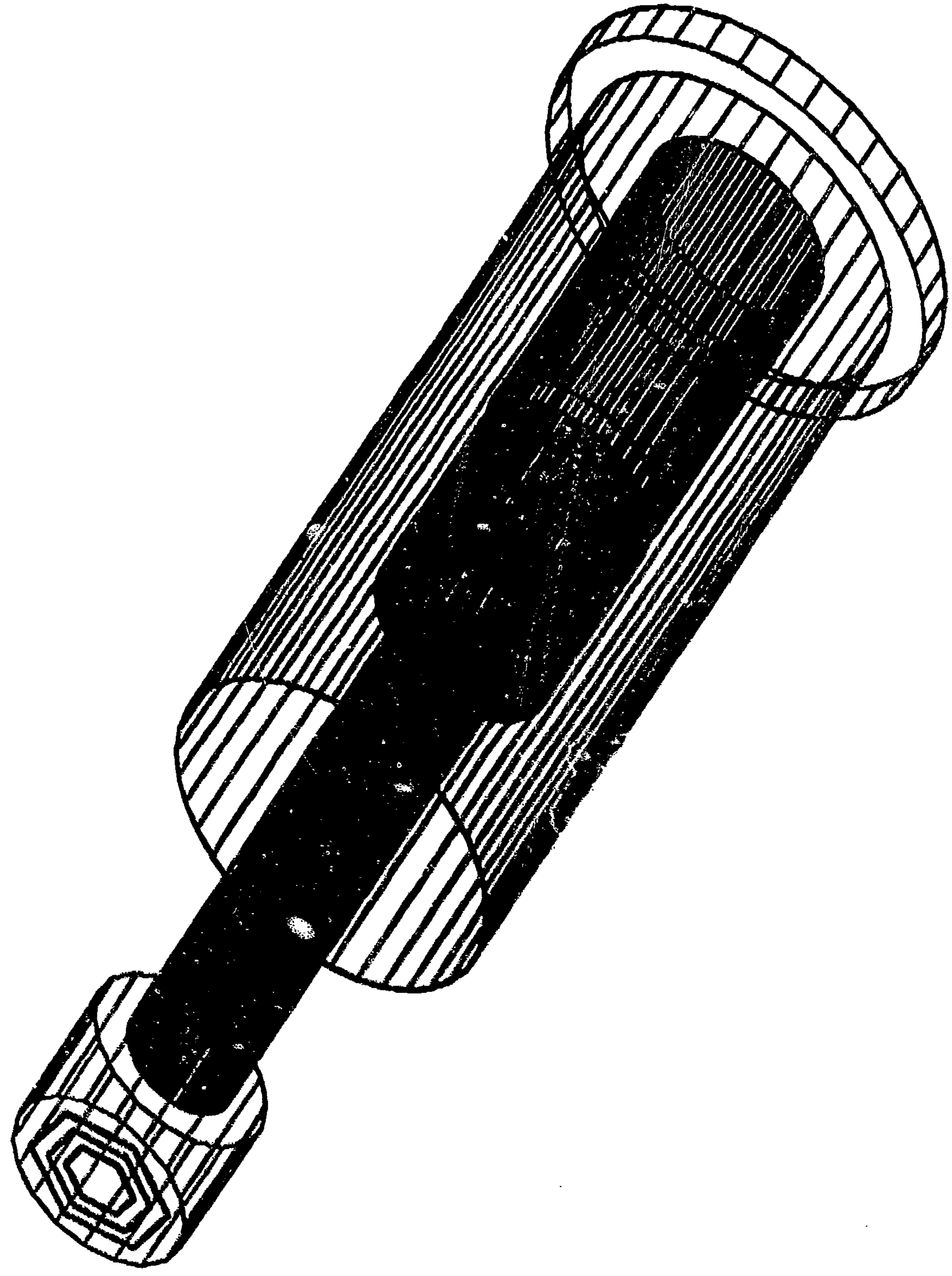


FIGURE 6 - THE ADJUSTABLE NUT DRIVER TOOL MECHANISM

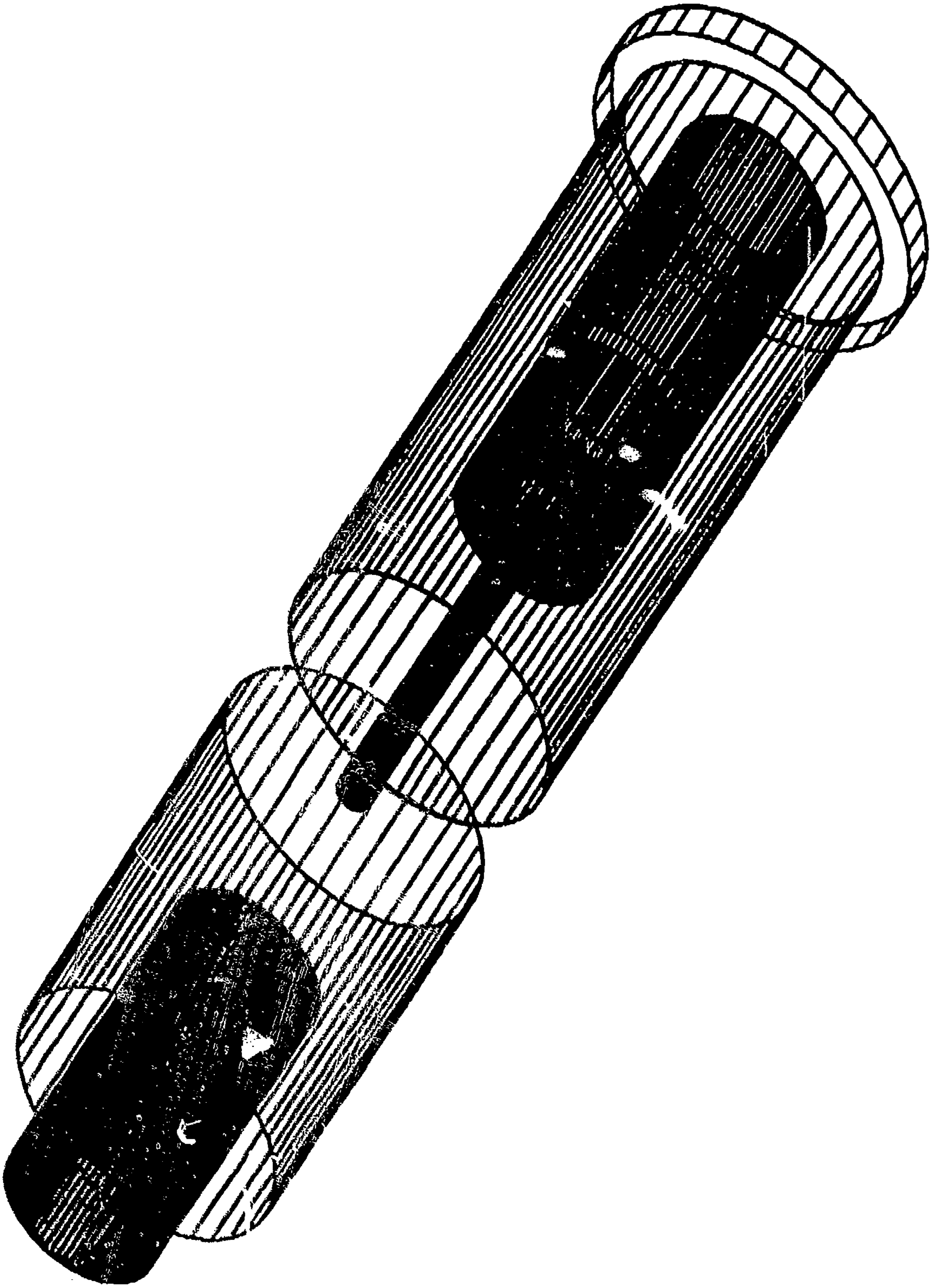


FIGURE 7 - THE IMPACT MECHANISM

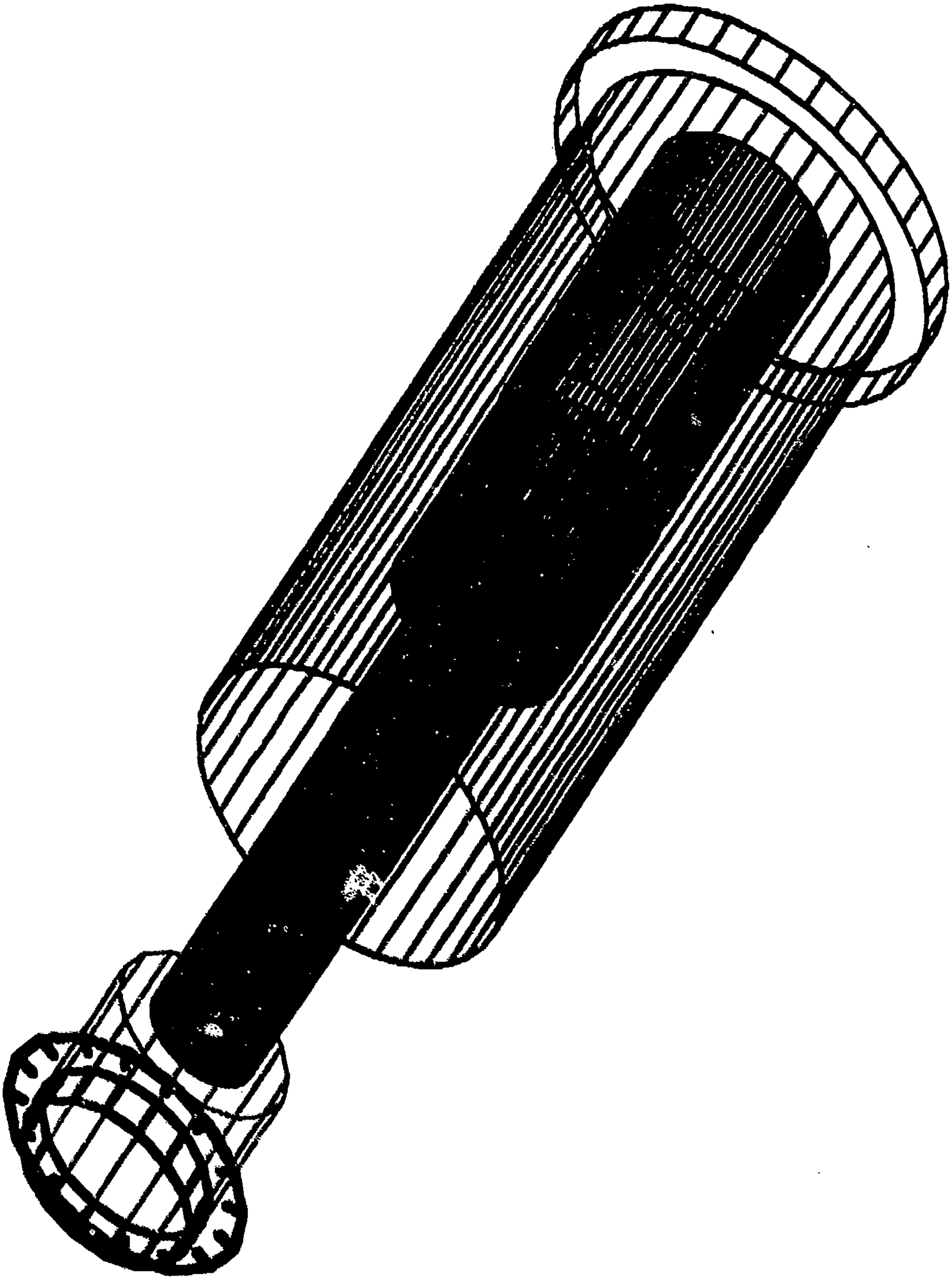


FIGURE 8 - THE ROTARY SAWING MECHANISM

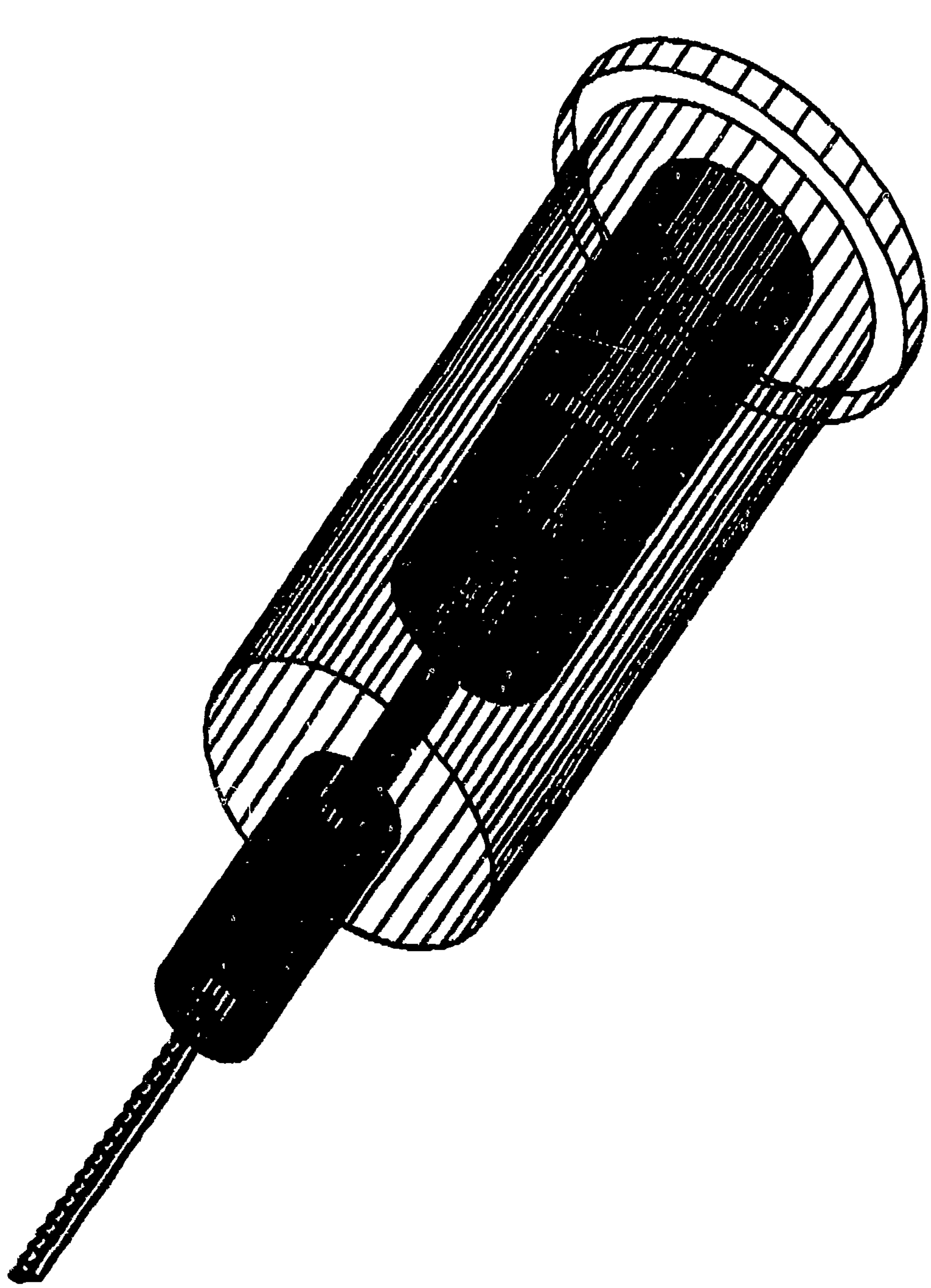
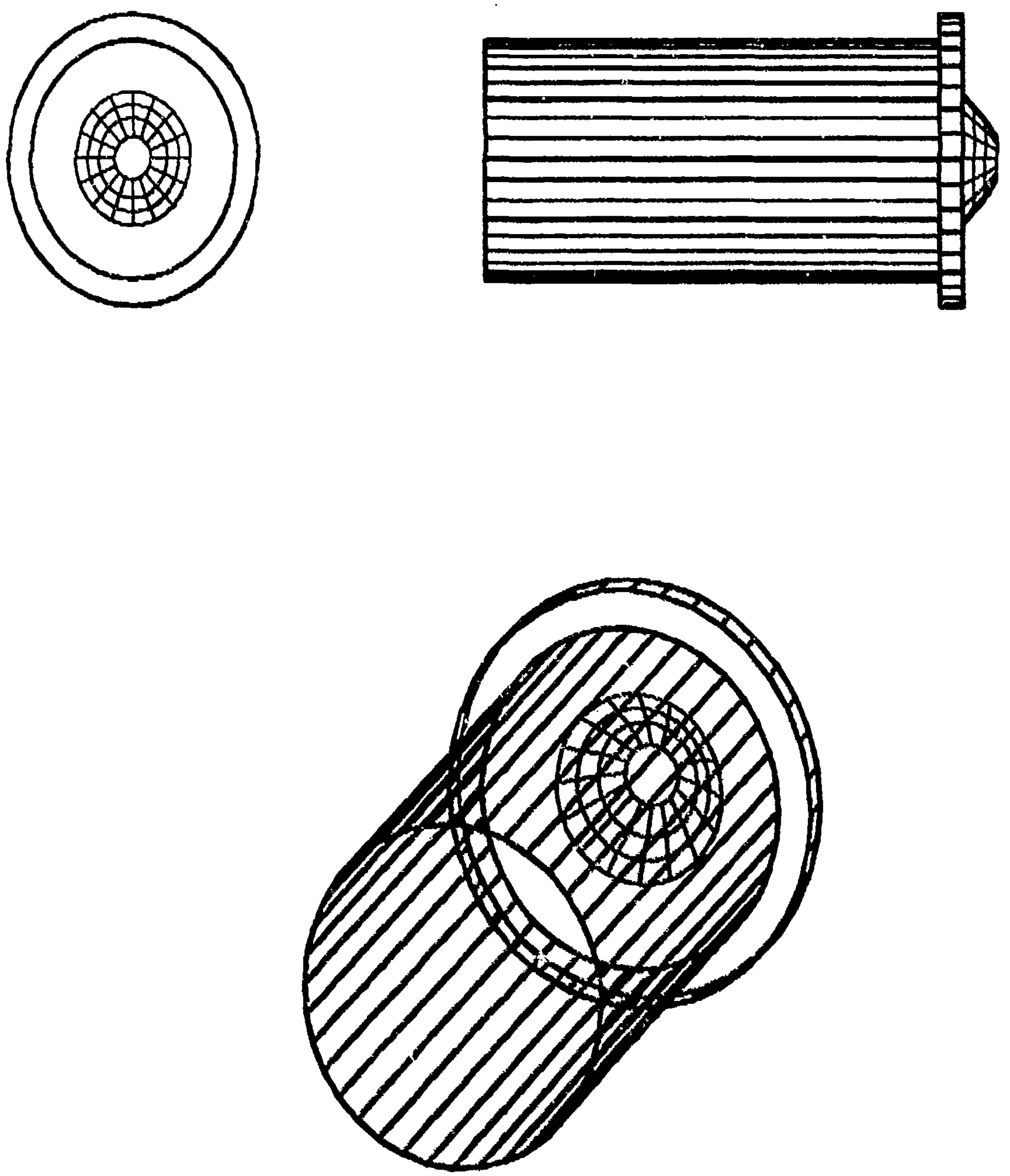


FIGURE 9 - THE RECIPROCATING SAW MECHANISM



Reception (Marriott Ballroom)

Chair: G.L. Workman, University of Alabama in Huntsville

Speaker: Joe Engelberger
Transitions Research Corporation (TRC)

Mr. Engelberger is President of Transitions Research Corporation (TRC), a young automation technology corporation in Danbury Connecticut specializing in service industry applications of robots. Mr. Engelsberger has B.S. and M.S. degrees in physics from Columbia University. He is mot widely known for helping to establish robotics into industrial markets by founding Unimation, Inc., and providing the PUMA robot family as the company's chief product. He led the company until just before its acquisition by Westinghouse Corporation and for a while primarily served as a consultant. His current interests at TRC include a thrust to broaden the applicability of robotic systems to a larger industrial as well as domestic base than that existing now.

Session V Program A

Robotic Systems

Chair: Ken Fernandez, NASA/MSFC

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Keynote Speaker: J. W. Littles, Director
Science and Engineering,
MSFC

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INSERTION WITH TWO COORDINATED ROBOT ARMS

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ABSTRACT

Much work has been done on the assembly of parts requiring implementation of a "peg in the hole" procedure using a single robotic manipulator guided by a force/torque transducer mounted near its end effector. In tasks such as the assembly of large structures, it may not be feasible for the object to be manipulated by a single robot. Two (or more) robots can more easily share the load and provide accurate end point guidance for parts mating. Force/torque sensing at each robot can support the required functions of relieving constraint forces and insertion guidance. This paper shows how information from the sensors is divided into feedback signals for these functions in a stable manner. A design example of such a system is given.

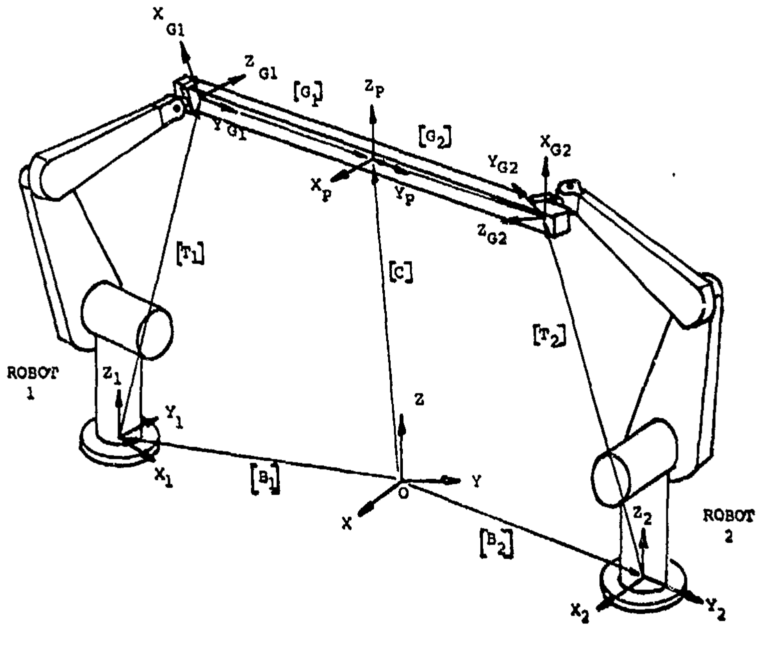
INTRODUCTION

In the assembly of large space structures, it is necessary to manipulate a single workpiece using multiple robot arms. This may occur when a relatively large workpiece must be located with great accuracy. Cooperating robot manipulators are also used in situations when the mass of the workpiece exceeds the capabilities of a single manipulator.

The control approach required for multi-arm manipulation differs significantly from that used in autonomous robotic operation. When two arms grasp a single workpiece, the resulting structure forms a closed kinematic chain. The number of actuators in this new structure is greater than the minimum needed to position the workpiece. This redundancy can result in the creation of constraint forces within the workpiece. Such a condition is brought about when position or orientation errors caused by manipulator miscalibration, grip point slippage, or similar effects cause interaction between the various actuators in each arm. These forces may be of sufficient mangnitude to make accurate positioning of the workpiece difficult to achieve.

One method of relieving constraint forces utilizes force/torque transducers located at each gripper to measure these forces, and to estimate from this information the magnitude and direction of trajectory and orientation errors that will compensate for the errors [1]. Previous work has also shown that force/torque sensors can be used to implement active compliance for insertion of a rod into a hole [2]. It seems quite feasible that the same force/torque sensors can be used for both tasks, and, in addition, for balancing the load between the two manipulators.

The present paper presents a design for a controller to allow two robot arms to control a long object such as a beam, and insert one end of it into a connector. It is assumed that the connector takes the form of a socket and, when insertion is done correctly, is self locking. Primary guidance for both robot arms might be derived from a television camera until the beam comes into



MODEL OF TWO ROBOTIC ARMS GRASPING A COMMON OBJECT

Figure 1

close proximity to the connector. At this point, visual guidance is secondary, and force/torque feedback is used until locking occurs.

RELIEVING CONSTRAINT FORCES

Consider first the more general problem of relieving constraint forces when multiple arms grasp a common object. The development herein follows that given in [1]. A model of two robotic arms grasping an object is shown in Figure 1. An arbitrary space fixed coordinate frame OXYZ serves as a global reference while body-fixed local coordinate frames are attached to the base of each robot ($O_1X_1Y_1Z_1$ and $O_2X_2Y_2Z_2$), to each of the two grippers ($O_{G1}X_{G1}Y_{G1}Z_{G1}$ and $O_{G2}X_{G2}Y_{G2}Z_{G2}$), and to a point on the object being manipulated ($O_PX_PY_PZ_P$).

The relative position and orientation of coordinate frames is described using homogeneous transform techniques developed by Hartenberg and Devavit [3]. Let $[B_1]$ and $[B_2]$ represent transforms relating the base frames of each robot to the global frame while $[G_1]$ and $[G_2]$ relate the gripper coordinate frames to their respective robot's base. The location of a reference position on the object being manipulated in the global frame is designated at any particular instant in time by the transform [C]. In order for the manipulators to move the object through a desired trajectory, each of the two manipulator controllers must implement its own path represented by

$$[T_1] = [B_1]^{-1}\,[C]\,[G_1]^{-1} \qquad (1)$$

$$[T_2] = [B_2]^{-1}\,[C]\,[G_2]^{-1} \qquad (2)$$

It can be seen that the success of multi-arm manipulation is heavily dependent on one's knowledge of the transforms $[B_1]$, $[B_2]$, $[G_1]$, and $[G_2]$. While the manipulator itself may be accurately calibrated, its position with respect to the global frame, and also the position of the grip points on the object may not be known to high accuracy.

The errors introduced can be represented by two vectors in homogeneous coordinates

$$[E_1] = [T_{1s}]^{-1} \; [T_{1a}] \tag{3}$$

$$[E_2] = [T_{2s}]^{-1} \; [T_{2a}] \tag{4}$$

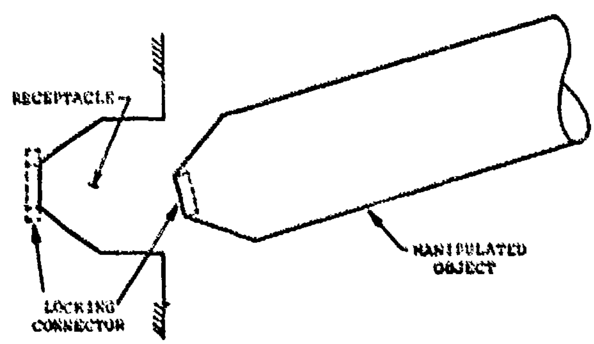
where the subscripts a and s refer to the specified and desired transformations. It is possible to compensate for one of these errors by modifying positional guidance. However, the error $[E_2]$ will cause constraint reactions to be developed within the structure being manipulated, which can result in undesireable deformations of that structure. This is especially true in space applications, where the object being manipulated is sometimes more flexible than the manipulators.

Constraint reactions may also result from the static loading associated with the weight of the workpiece (when in a gravity field), from dynamic loads corresponding to the rigid body motion of the system as well as from the flexural vibrations of the structure, and from other sources (actuator compliance, stiction, damping, contact with environment, etc.). For purposes of this investigation, it has been assumed that the robots are moving at relatively low speeds and that the constraint forces due to errors in the $[B_1]$, $[B_2]$, $[G_1]$, and $[G_2]$ matrices are large when compared to other sources.

INSERTION ALGORITHMS

In order for the object to properly mate with its end connector, an insertion algorithm must be synthesized. Previous efforts [2] have shown that insertion of a peg with a single manipulator using active control is feasible if the contact process is analyzed and broken down into different regions. A separate control strategy is specified for each region. The number of regions, and the control stratagies to be utilized, is dependent on the geometry of the particular problem.

In the present situation, it is assumed that the connector into which the object must be mated was designed for "easy insertion". The insertion algorithm must provide translatory and rotational guidance to complete the insertion; however, the object need be inserted only a short distance before locking occurs. To simplify translatory guidance, the object is tapered for a short distance at its end. The object and locking connector is shown in Figure 2.



THE OBJECT BEING MANIPULATED AND THE LOCKING CONNECTOR

Figure 2

A short insertion distance implies that all points of contact between the object and the connector are clustered at the object's end; a priori knowledge of the point of contact is beneficial in constructing the control strategy. The insertion process was divided into two regions and a control algorithm was constructed for each:

o Contact occurs along the tapered portion of the object end

When contact occurs in this region, the taper of the object causes a component of the contact force to be transmitted axially along the object. For a circular object, a radial force is also transmitted inward toward the axis of the object which can be resolved into cartesian components which are dependent on the orientation of the coordinate system. The forces of contact can be resolved into an equivalent force system which is located at a fixed reference point at the center of the crown of the taper; see Figure 2. The forces at this point will have the same magnitude and direction as those at the point of contact; moments will be present at the reference point to account for the change in position. These moments will be small because of the short length of the tapered system.

o Contact occurs after the shaft has entered the connector, but before connection occurs

If the object partially inserts into the connector and jams, then the orientation of the object is incorrect. This is entirely equivalent to having a third "gripper" holding the object, located at the previously defined reference point. Partial insertion and jamming causes a deformation of the object. This deformation can only be relieved by proper position and orientation of the object with respect to the connector. If the forces and torques at the two robot grippers a... continually minimized subject to the constraint that the position of the object within the connector is correct, then insertion can be completed as the object is reoriented.

Insertion is accomplished by estimating the forces at the reference point from the force/torque readings at the grippers, and applying appropriate correction:

- Using a beam model gripped at two points, forces and torques are calculated at the reference point from the gripper readings.

- If the axial force is significant, contact is assumed to occur along the tapered portion o. the object, and control proceeds by applying discrete translatory corrections in the direction of the radial component of the sensed force, and relieving constraint forces at the outermost gripper.

- If the axial force is small, contact is assumed to occur after a partial insertion, and control proceeds by applying the corrective translations and orientations necessary to relieve constraint forces at both grippers.

CONTROLLER ALGORITHMS

The relation between constraint forces and resulting kinematic error can be determined using conventional structural analysis techniques. The links of each manipulator and the object being manipulated can be modeled using an appropriate global stiffness matrix [K] where the following relationship exits between constraint reactions and nodal deformations

$$\{F\} = [K]\{\Delta\} \qquad (5)$$

where

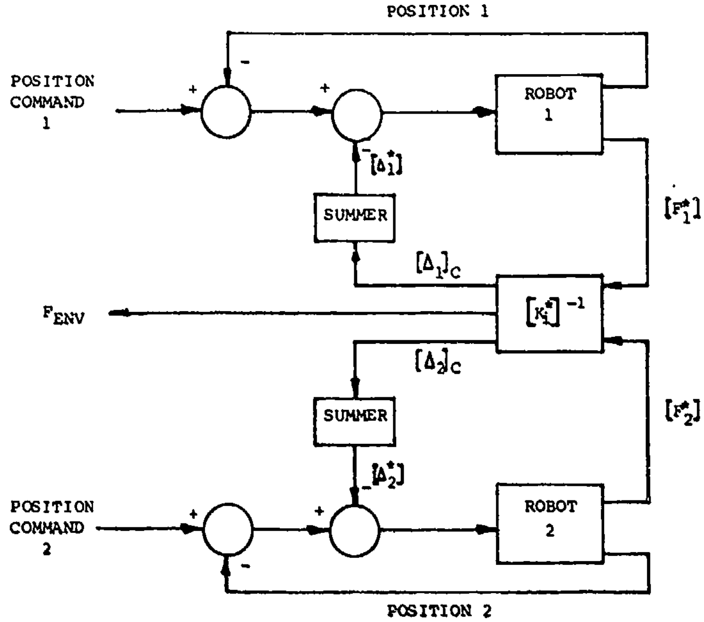
$\{F\}$ is a column vector of nodal reactions (forces and moments),

$[K]$ is a global stiffness matrix, and

$\{\Delta\}$ is a column vector of nodal displacements.

The matrix $[K]$ is in general singular. However, when the appropriate compatibility conditions are imposed, a nonsingular version of $[K]$ can be constructed.

The control strategy is based upon inverting (5) to determine the nodal



BLOCK DIAGRAM OF THE CONTROLLER

Figure 3

errors $\{\Delta\}$ corresponding to a known reaction vector $\{F\}$. The nodal errors are corrected by appropriate trajectory adjustments in each of the manipulators.

The technique was modified to account for the expected uncertainty in the coupling matrix components and the presence of errors in the transducer information. An iterative strategy is employed which converges to the correct $\{\Delta\}$ when $[K]$ is incorrect but suitably bounded, and $\{F\}$ is biased and noisy.

The controller design is shown in Figure 3. Matrix $[K^*]$ represents an approximation of $[K]$. A cumulative estimation of $\{\Delta\}$ is found using the expression

$$\{D^*_{n+1}\} = \{D^*_n\} + [K^*]^{-1} \{F\} \tag{6}$$

where $\{D^*_n\}$ is the estimate of $\{\Delta\}$ obtained after n iterations. The force/torque reading at the n^{th} iteration may be expressed by

$$\{F\} = [K] \{\delta_n\} \tag{7}$$

where

$$\{\delta_n\} = \{D^*_n\} - \{\Delta\} \tag{8}$$

The error at any iteration is found by combining (6) and (7) to obtain:

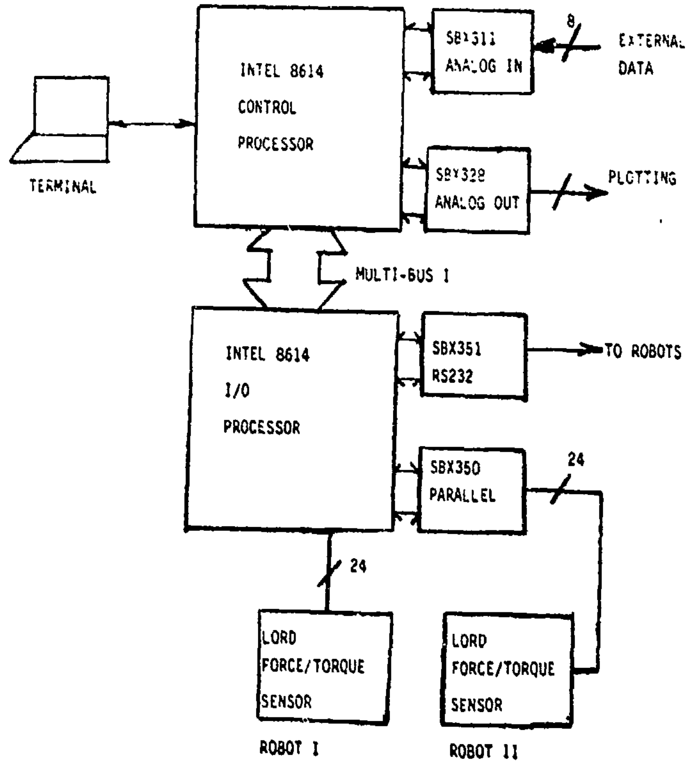
$$\{\delta_{n+1}\} = (I-[K^*]^{-1}[K]) \{\delta_n\} \tag{9}$$

The above will converge if

$$|| I - [K^*]^{-1}[K] || < 1. \tag{10}$$

CONTROLLER DESIGN

The controller will be implemented with two Lord 15/50 force/torque transducers, one on each gripper of two PUMA 560 robots. Computations will be performed on two INTEL 8614 microprocessor boards, one dedicated to I/O between the sensors and the VAL II language on the robots. The second 8614 board will perform the calculations. A diagram of this system is shown in Figure 4.



HARDWARE INTERCONNECTION DIAGRAM

Figure 4

To implement the controller, $[K^*]$ was obtained by considering the object being manipulated to be a beam element with three nodes corresponding to the two points of contact of the gripper, and the reference point of contact. The forces and moments on the object at its three nodes can be represented by

$$[F] = (F_{x1}, F_{y1}, F_{z1}, M_{x1}, M_{y1}, M_{z1}, F_{x2}, F_{y2}, F_{z2}, M_{x1}, M_{y2}, M_{z2}, F_{xr}, F_{yr}, F_{zr}, M_{xr}, M_{yr}, M_{zr})^T \quad (11)$$

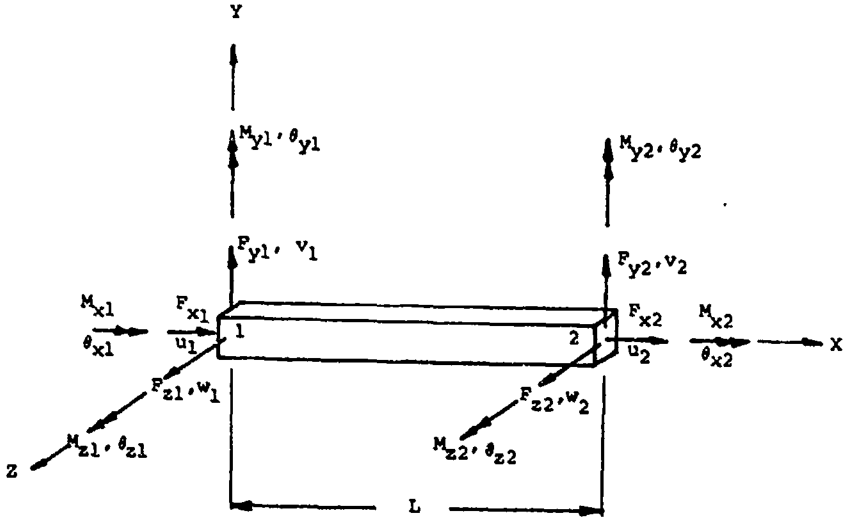
and the corresponding displacement vector is represented by

$$[D] = (u_1, v_1, w_1, \theta_{x1}, \theta_{y1}, \theta_{z1}, u_2, v_2, w_2, \theta_{x2}, \theta_{y2}, \theta_{z2}, u_r, v_r, w_r, \theta_{xr}, \theta_{yr}, \theta_{zr})^T \quad (12)$$

where F_x, F_y, F_z are forces one their respective cartesian axes, M_x, M_y, M_z are moments about these axes, u, v, w are displacements about the x, y, and z axes, and θ_x, θ_y, θ_z represent angular deviations these axes. It is possible to construct a stiffness matrix relating these quantities using beam theory. A sample beam element is shown in Figure 5, and its stiffness matrix is shown in Figure 6. The assembled stiffness matrix is of dimension 18, larger than is feasible to reproduce here. From the definition of the problem, it is assumed that the reference point on the object, i.e., that point where the object meets the connector, is at its proper location. This implies a set of boundary conditions for the system, and the original stiffness matrix may be partitioned into two matrices, one relating forces at the gripper to gripper error (the $[K^*]$ matrix) and the other (called the $[K']$ matrix) predicting the forces at the reference point. The matrix $[K^*]$ will now be invertible yielding the following relations

$$[D'_{n+1}] = [D'_n] + [K^*]^{-1} [F1] + [D'_{r1}]$$

$$[F2] = [K'] [K^*]^{-1} [F1] \quad (13)$$



BISYMMETRICAL BEAM ELEMENT

Figure 5

where

$[F1] = (F_{x1}, F_{y1}, F_{z1}, M_{x1}, M_{y1}, M_{z1}, F_{x2}, F_{y2}, F_{z2}, M_{x2}, M_{y2}, M_{z2})^T$

$[D'] = (u_1, v_1, w_1, \theta_{x1}, \theta_{y1}, \theta_{z1}, u_2, v_2, w_2, \theta_{x2}, \theta_{y2}, \theta_{z2})^T$

$[F2] = (F_{xr}, F_{yr}, F_{zr}, M_{xr}, M_{yr}, M_{zr})^T$ and

$[D'_{r1}]$ is the correction to be applied when contact is made with tapered portion of the object.

The control algorithm consists of computing [F2] from (13) and determining whether F_{zr} lies above a threshold that would indicate contact on the tapered portion of the object. If so, a the object is moved a small discrete amount $[D'_{r1}]$ which is proportional to the axial insertion velocity of the object and in a direction to alleviate the contact force. $[D'_{r1}]$ contains displacements only, and the net displacement is reflected to each gripper using appropriate transforms.

CONCLUSIONS

This paper outlines control algorithms for two robots inserting an object into a connector that is currently being implemented. The algorithm is based on two successful previous experiments, one to relieve stress caused by two robots gripping an object, and the second to insert an object into a hole using active force/torque control. The technique employs a network of force/torque sensors to implement force feedback used by both tasks.

The system described is currently under construction, and it is hoped that some data on its effectiveness will soon be available.

$$
\begin{bmatrix} F_{x1} \\ F_{y1} \\ F_{z1} \\ M_{x1} \\ M_{y1} \\ M_{z1} \\ \hline F_{x2} \\ F_{y2} \\ F_{z2} \\ M_{x2} \\ M_{y2} \\ M_{z2} \end{bmatrix} = E \left[\begin{array}{c:c} [S_1] & [S_2] \\ \hdashline [S_3] & [S_4] \end{array} \right] \begin{bmatrix} u_1 \\ v_1 \\ w_1 \\ \theta_{x1} \\ \theta_{y1} \\ \theta_{z1} \\ u_2 \\ v_2 \\ w_2 \\ \theta_{x2} \\ \theta_{y2} \\ \theta_{z2} \end{bmatrix}
$$

where

$$
[S_1] = \begin{bmatrix} A/L & 0 & 0 & 0 & 0 & 0 \\ 0 & 12I_z/L^3 & 0 & 0 & 0 & 6I_z/L^2 \\ 0 & 0 & 12I_y/L^3 & 0 & -6I_y/L^2 & 0 \\ 0 & 0 & 0 & J/2(1+\nu)L & 0 & 0 \\ 0 & 0 & -6I_y/L^2 & 0 & 4I_y/L & 0 \\ 0 & 6I_z/L^2 & 0 & 0 & 0 & 4I_z/L \end{bmatrix}
\qquad
[S_2] = \begin{bmatrix} -A/L & 0 & 0 & 0 & 0 & 0 \\ 0 & -12I_z/L^3 & 0 & 0 & 0 & 6I_z/L^2 \\ 0 & 0 & -12I_y/L^3 & 0 & -6I_y/L^2 & 0 \\ 0 & 0 & 0 & -J/2(1+\nu)L & 0 & 0 \\ 0 & 0 & 6I_y/L^2 & 0 & 2I_y/L & 0 \\ 0 & -6I_z/L^2 & 0 & 0 & 0 & 2I_z/L \end{bmatrix}
$$

$$
[S_3] = \begin{bmatrix} -A/L & 0 & 0 & 0 & 0 & 0 \\ 0 & -12I_z/L^3 & 0 & 0 & 0 & -6I_z/L^2 \\ 0 & 0 & -12I_y/L^3 & 0 & 6I_y/L^2 & 0 \\ 0 & 0 & 0 & -J/2(1+\nu)L & 0 & 0 \\ 0 & 0 & -6I_y/L^2 & 0 & 2I_y/L & 0 \\ 0 & 6I_z/L^2 & 0 & 0 & 0 & 2I_z/L \end{bmatrix}
\qquad
[S_4] = \begin{bmatrix} A/L & 0 & 0 & 0 & 0 & 0 \\ 0 & 12I_z/L^3 & 0 & 0 & 0 & -6I_z/L^2 \\ 0 & 0 & 12I_y/L^3 & 0 & 6I_y/L^2 & 0 \\ 0 & 0 & 0 & J/2(1+\nu)L & 0 & 0 \\ 0 & 0 & 6I_y/L^2 & 0 & 4I_y/L & 0 \\ 0 & -6I_z/L^2 & 0 & 0 & 0 & 4I_z/L \end{bmatrix}
$$

and

A = area $\qquad$ I, J = moments of inertia $\qquad$ L = length

E = elastic modulus $\qquad$ ν = Poisson's ratio

u, v, w = displacement components $\qquad$ θ = angular displacement

BEAM ELEMENT STIFFNESS MATRIX

Figure 6

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ORBITAL MANEUVERING VEHICLE (OMV) REMOTE SERVICING KIT

May 1988

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ABSTRACT

With the design and development of the Orbital Maneuvering Vehicle (OMV) progressing toward an early 1990's initial operating capability (IOC), a new era in remote space operations will evolve. The logical progression to OMV front end kits would make available in-situ satellite servicing, repair, and consummables resupply to the satellite community. Several conceptual design study efforts are defining representative kits (propellant tankers, debris recovery, module servicers); additional focus must also be placed on an efficient combination module servicer and consummables resupply kit. A remote servicer kit of this type would be designed to perform many of the early maintenance/resupply tasks in both nominal and high inclination orbits (28.5 deg and 90+ deg). The kit would have the capability to exchange Orbital Replacement Units (ORU's), exchange propellant tanks, and/or connect fluid transfer umbilicals. Necessary transportation system functions/support could be provided by interfaces with the OMV, Shuttle (STS), Space Station (SS), or Expendable Launch Vehicle (ELV).

INTRODUCTION

With the deployment of the NASA Orbital Maneuvering Vehicle (OMV), many spacecraft services will be available in the early 1990's. The OMV's primary missions are of a retrieval and delivery nature based at the Space Transportation System (STS) or Space Station (SS) (Figure 1). In addition, in-situ spacecraft servicing may be performed by the OMV with special purpose front end mission kits. The OMV kits would be capable of performing remote maintenance of spacecraft. The OMV will be capable of providing propulsion, attitude control, data handling and communication, and power for the Smart Front End (SFE) kit.

The remote servicing of spacecraft falls into two main categories: replacement of failed elements [orbital replacement units (ORU's), batteries, etc.] or consummables resupply (propellant, pressurant, etc.). The capability to replace failed modules and resupply consummables offer satellite programs a reduced operating cost when compared with the replacement of an entire satellite.

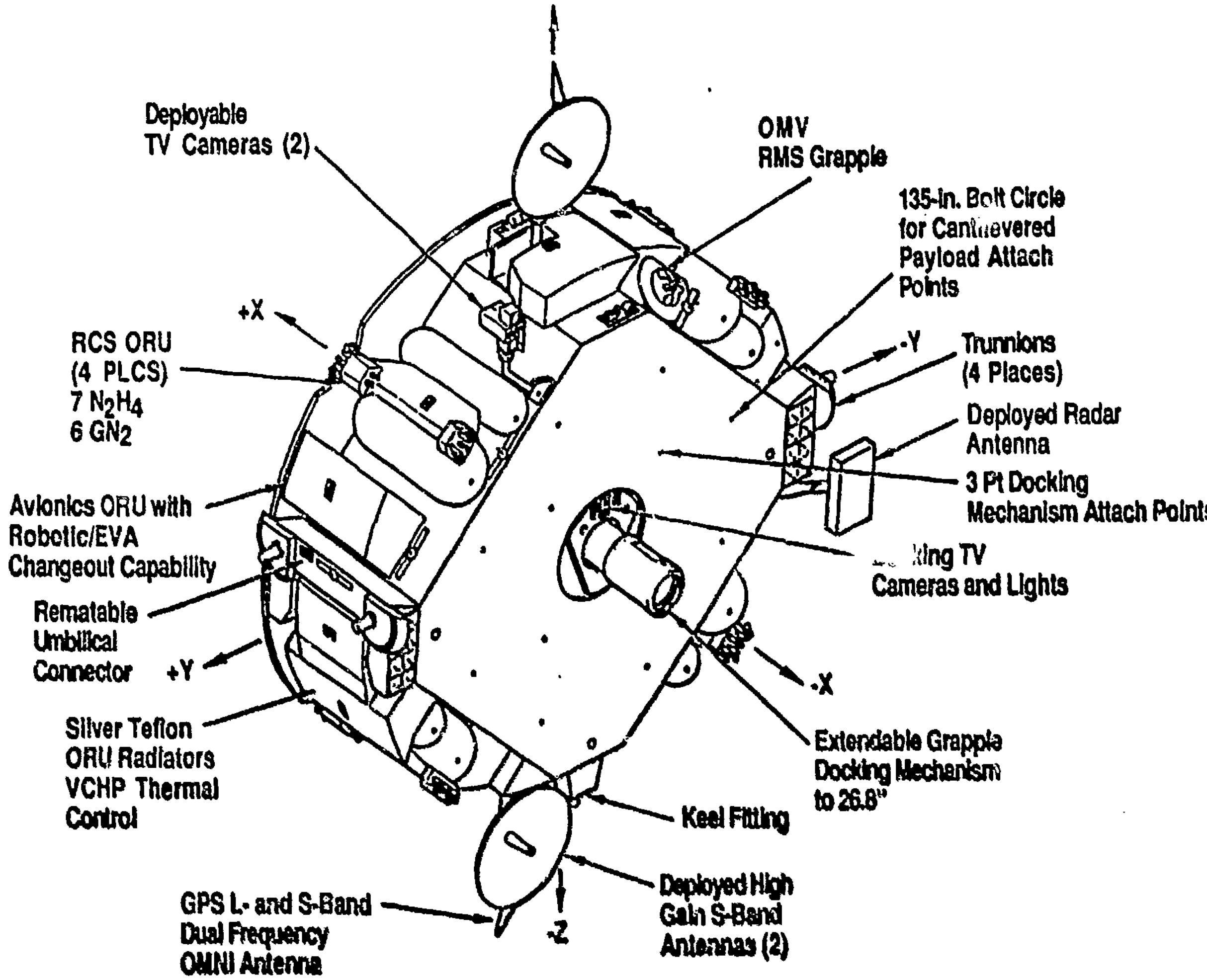

Figure 1. ONV Configuration, View of Front Face[1]

REQUIREMENTS

The requirements on the SFE kit fall into three categories: capability, control, and interfaces. The SFE kit must be able to remotely repair, maintain, upgrade, and return spacecraft modules. Additionally, resupply of spacecraft consummables such as hydrazine, bipropellant, helium, nitrogen, and cryogens is required. The fluid system interfaces must be minimal leak connectors and automated/Extravehicular Activity (EVA) couplings. The SFE kit will be remotely operable in an autonomous (man supervised) mode. The backup control would be the teleoperations mode. The ORU interfaces on the SFE/spacecraft would be operable by the servicer mechanism, by EVA, and by ground operations. The SFE kit would interface with the STS, SS, Expendable Launch Vehicle (ELV), and primarily the ONV. The SFE must utilize and interface with the ONV subsystems.

DESIGN[2]

The SFE conceptual system configuration is shown in Figure 3. The SFE mass and volume (700 lbs.dry, 176 in. diameter) characteristics make it feasible for

1. Users Guide for the Orbital Maneuvering Vehicle, MSFC, October 1987.

2. Based on Contract NAS8-35625, Servicer System User's Guide, Martin Marietta, July 1986.

CAPA^IL ITY

- MODULE EXCHANGE OF ORU'S
  - REPAIR
  - MAINTAIN
  - UPGRADE
  - RETURN
- RESUPPLY
  - HYDRAZINE
  - MMH/NTO
  - HELIUM } PRESSURANT
  - NITROGEN } PRESSURANT
  - CRYOGENS

CONTROL

- AUTONOMOUS
- TELEOPERATIONS BACKUP

INTERFACES

- SFE INTERFACES OPERABLE BY
  - SERVICER
  - EVA
  - GROUND
- SFE INTERFACES TO VEHICLES
  - OMV (PRIMARY)
  - STS
  - S/S
  - ELV

Figure 2. SFE Requirements

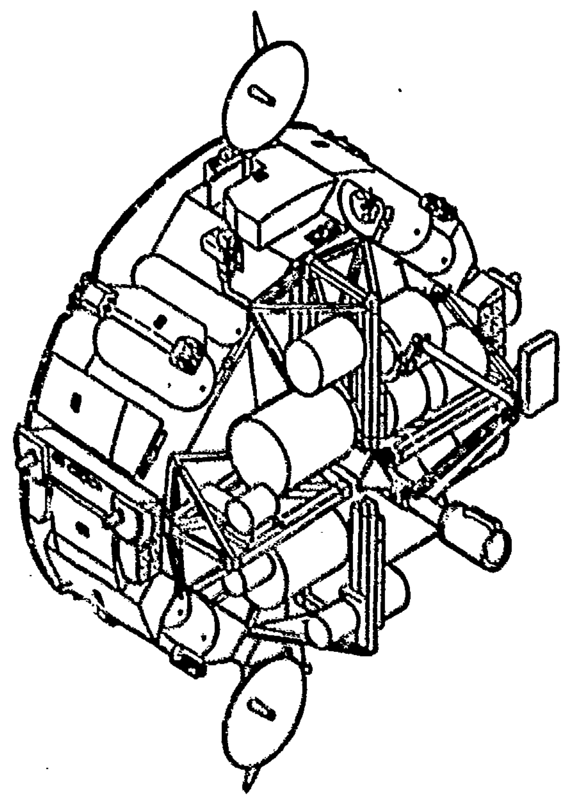

Figure 3. SFE Design

various transportation elements. The SFE design has two major components: the servicer mechanism arm(s) and a module/tank storage rack.

The arm(s) design consists of a pivoting system that may accommodate axial a radial module exchange, and is adaptable to various module configurations and alt native uses. The main arm components are a shoulder roll drive, a shoulder pitch drive, an upper arm member, an elbow roll drive, a forearm, a wrist pitch drive, a wrist roll drive, and an end effector. The arm has 6 degrees-of-freedom and limited dexterity. The end effector concept would be designed to: mate with interface mechanisms and fluid interface units, to operate a latching mechanism, and provide an electrical connection.

The purpose of the storage rack is to provide structural support for the replacement modules, servicer mechanism, and docking probe. The storage rack aft end interfaces directly with the OMV. Compatibility with the STS is obtained by the addition of a flight support system. The 176 in. diameter cylindrical envelope should make the storage rack compatible with most of the feasible carrier vehicles. The basic storage rack configuration is a truss consisting of four frames that connect the central transition fitting to the OMV attachments and that supports the modules through the interface mechanisms. The servicer mechanism attaches to the transition fitting. The outer ends of the four trusses are stabilized through sets of braces.

The conceptual design of the SFE kit was based on the simple nature of the module exchange and fluid resupply tasks. The activities of remove, flip, relocate, and insert modules/servicing attachments, when combined with pre-defined arm(s) trajectories, were used to create a simple design in terms of mechanism configuration, control system design, and operations approach. The supervisory mode of control would be the normal mode of operation. It consists of automated sequences of trajectories that are determined before flight. The operator assisted mode is a modification of the supervisory mode in which the operator provides inputs to the computer for each action of the servicer in its performance. A manual backup mode would be provided in the event of failure of the other control modes.

The conceptual design shown is based on the Integrated Orbital Servicing System (IOSS) 1-g prototype operating at NASA Marshall Space Flight Center (MSFC). The single arm design can perform most of the early defined servicing tasks (ORU exchange, fluid resupply). If further analysis and safety/redundancy requirements prove to be drivers, an additional arm could be connected to the shoulder. The second arm, with additional dexterity, could perform more difficult tasks (solar array changeout). Eventual capability may evolve to a Flight Telerobotic Servicer (FTS) class which could perform many servicing tasks, planned or unplanned. A FTS would be accommodated by either a hard mount to the SFE storage rack or interfaced with the existing FSE arm.

SERVICING OPERATIONS

The primary mission of the SFE kit is to remotely exchange failed spacecraft modules and replenish spacecraft consummables. The servicer system should be operable in a variety of control modes and has the capability of performing its servicing functions when carried on various carrier vehicles. The spacecraft servicing will range from nominal to high inclination Low Earth Orbit (LEO). Additionally, the capability exists to service Geosynchronous Orbit (GEO) assets.

ORU module exchange is normally performed along two spacecraft directions. The first is an axial direction where the modules are moved parallel to the docking system centerline. The second is a radial direction where the modules move along a radius, or perpendicular to the docking system centerline. Basic module exchange provides latitude in servicing missions since no adapter hardware is required for the servicer end effector to perform the module exchange. In all servicer functions, the first step in performing servicing of a satellite is to unstow the docking mechanism followed by a checkout of the entire servicer system. Then the front end kit is docked to the spacecraft using the OMV docking probe. The SFE arm then positions and orients the end effector for module exchange. The end effector, moved under control of the system computer, is positioned so the SFE kit TV camera can acquire and verify the target. The arm moves the end effector in and it mates to the interface mechanism on the ORU. Upon mating with the module, the electrical and mechanical interfaces between the ORU and spacecraft are disconnected using the mechanical drive of the end effector. The module is then removed from the spacecraft. Upon removal, the ORU would be stored in a vacant rack of the kit (a second arm could temporarily hold the spend ORU). An operating module is then placed in position on the spacecraft, similarly to the removal process, and all electrical and mechanical interfaces are verified. Following any module exchange, the servicer is ready to perform other functions or undock from the spacecraft. The basic module exchange process can accommodate a wide range of modules. Within the constraints of the SFE kit and the OMV, a single module could range up to a 40 in. cube and weigh approximately 400 lbs. Larger modules could be accommodated but require consideration with regard to the storage rack and the module exchange trajectory.[3]

The term fluid resupply denotes the replenishment of any fluid, either liquid or gas, involved in spacecraft systems. Spacecraft resupply can be achieved by several methods:

1. When servicing operation requires a large quantity of fluid, a dedicated tanker system, such as Orbital Spacecraft Consummables Recovery System (OSCRS) could be sandwiched between the OMV and the SFE.
2. When lesser amounts of fluid are required:
   a. Exchange of propellant tanks, i.e., treat tanks as ORUs.
   b. Carry small tanks in the kit storage rack as a supply vessel for the fluid transfer.
   c. Utilize the OMV residual propellants.

In the stored position, the fluid resupply module is flush with the front face of the SFE storage rack. The interface between the fluid resupply module and the SFE is simple, mechanical fastening system with electrical connections for control and monitoring functions. Integration of the fluid resupply module with the FSE is a simple operation which can be performed at the Space Station, at the STS bay, or on the ground, thus allowing operational flexibility. The fluid interface unit includes a set of fluid disconnects mounted on a translation device and connected to the resupply tanks by a flex hose. The translation device can be picked up and mated to the spacecraft interface by the servicer arm or mated automatically. During the fluid transfer operations the servicer arm can free itself from the fluid interface unit and be used for other tasks. However, the arm reach would be limited due

3. Servicer System User's Guide, Martin Marietta, July 1986.

to the hose connections. Fluid disconnects are used during fluid transfer to make temporary connection for the resupply operation.[4]

Initial servicing locations will consists of LEO operations, typically nominal (28.5 deg) and high (90 deg) inclinations. Nominal inclination satellites may be serviced by the SFE based at the STS or SS. Figure 4 shows a typical servicing scenario, (i.e.) Advanced X-Ray Astrophysics Facility) as well as elapsed mission time, for the STS based OMV/SFE. In this concept, the Orbiter would deliver the OMV/SFE to orbit and the OMV/SFE would transfer and mate with the target. The Orbiter would remain in orbit after deploying the OMV/SFE and await its return. After the servicing activity, the OMV/SFE would return to the Orbiter for its return to Earth. The total mission time is approximately 29 hr with 6 hr servicing time.

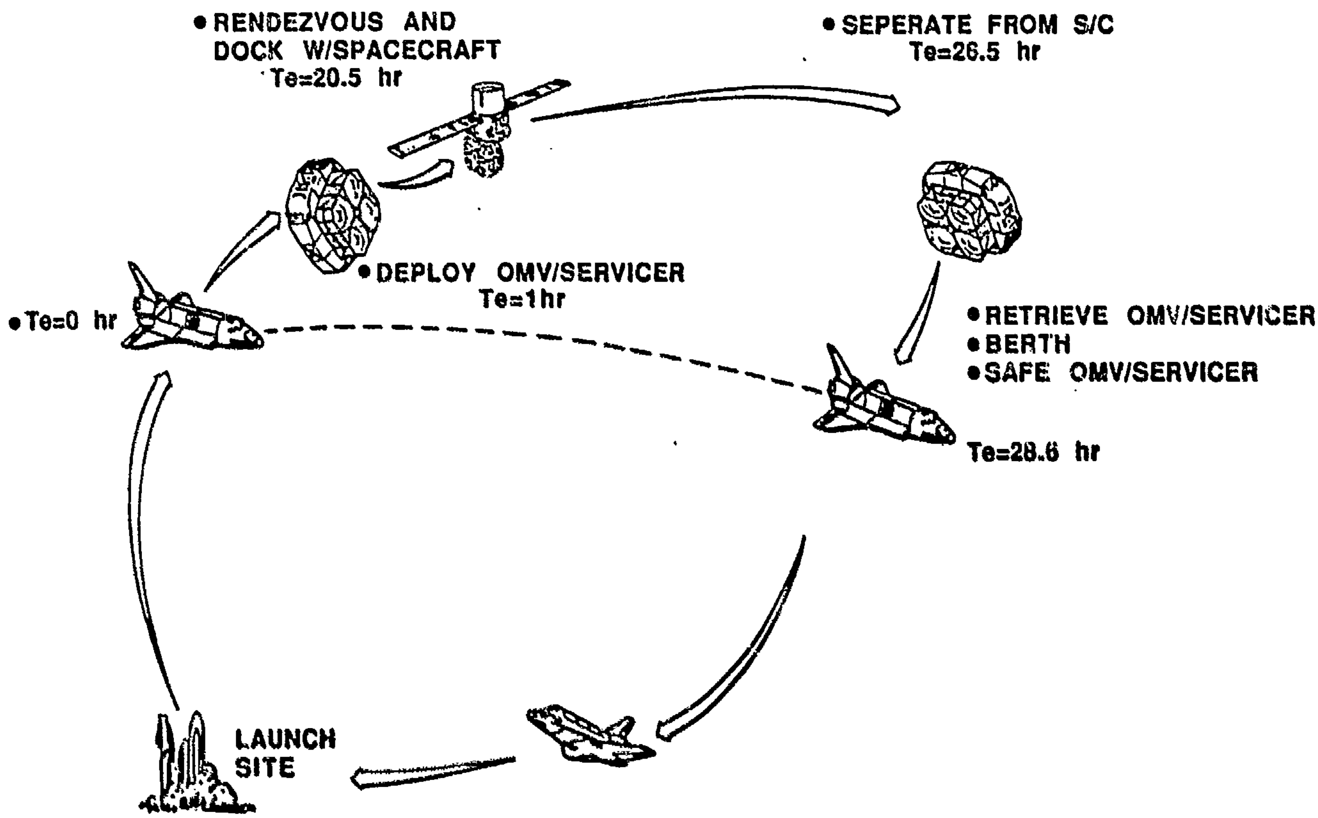

Figure 4. LEO (28.5 deg) Inclination Servicing

Figure 5 shows a typical high inclination servicing scenario (i.e., Earth Observation System polar platform), as well as elapsed mission time, for an ELV based SFE. In this concept, the OMV, or some version of the short range vehicle, would be based at a platform. An ELV would deliver the SFE into a stabilized orbit. The OMV would rendezvous with the SFE and deliver it to the target platform. After the servicing mission, the OMV/SFE could translate and service another asset or return to a base platform. Future deliveries may only include payload to be exchanged. The total mission time, for one asset, is approximately 15 hr with 6 hr servicing time. (Note: EOS used to generate timelines.) It should be noted that a

4. Fluid Resupply and Module Exchange Integration Analysis, Martin Marietta, December 1987.

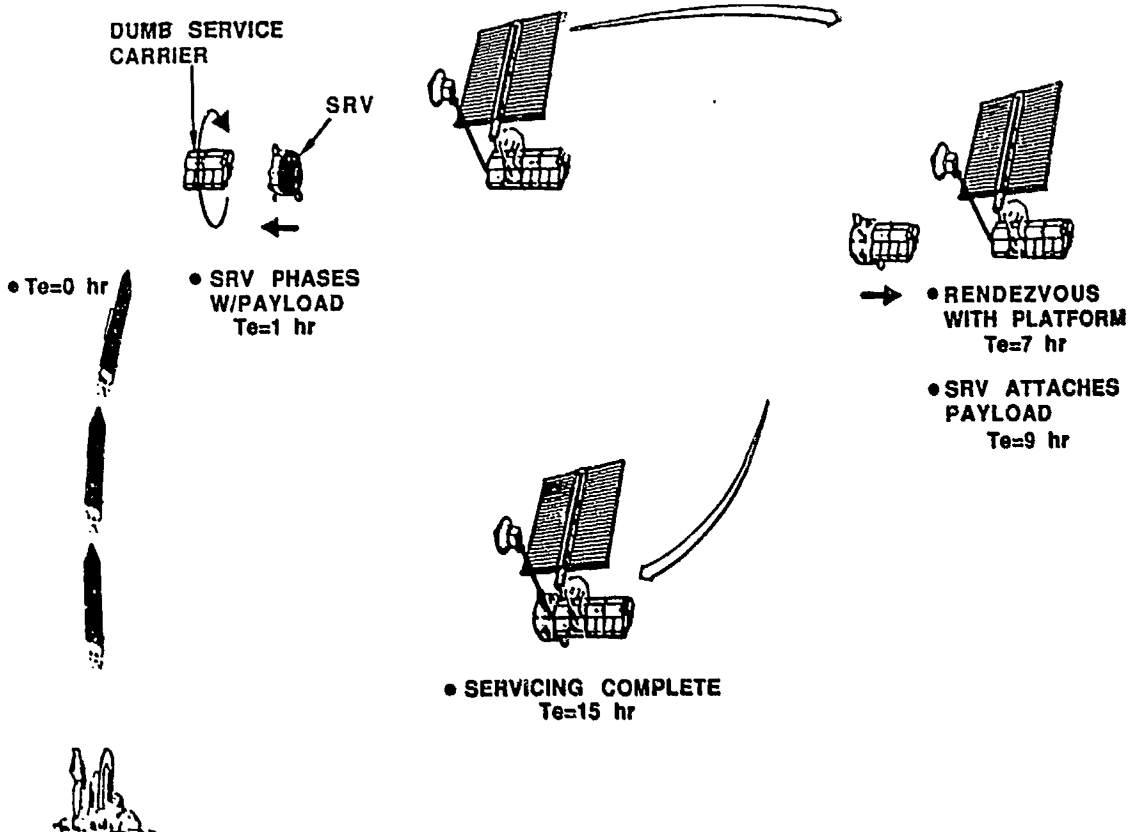

Figure 5. LEO (90 deg inclination) Servicing

Western Test Range (WTR) STS would follow an operational sequence similar to the nominal inclination operations.

SUMMARY

An OMV SFE kit will provide cost-effective, efficient on-orbit satellite servicing. Lower Earth orbit servicing will be available for many spacecraft requiring ORU exchange and consummables resupply. An initial SFE kit would be capable of preprogrammed and teleoperation tasks and interfacing with basic mechanisms. SFE evolution (Figure 6) may consist of a more dexterous servicer with an additional arm for more difficult tasks. Eventually, the capability to perform complex tasks will be available.

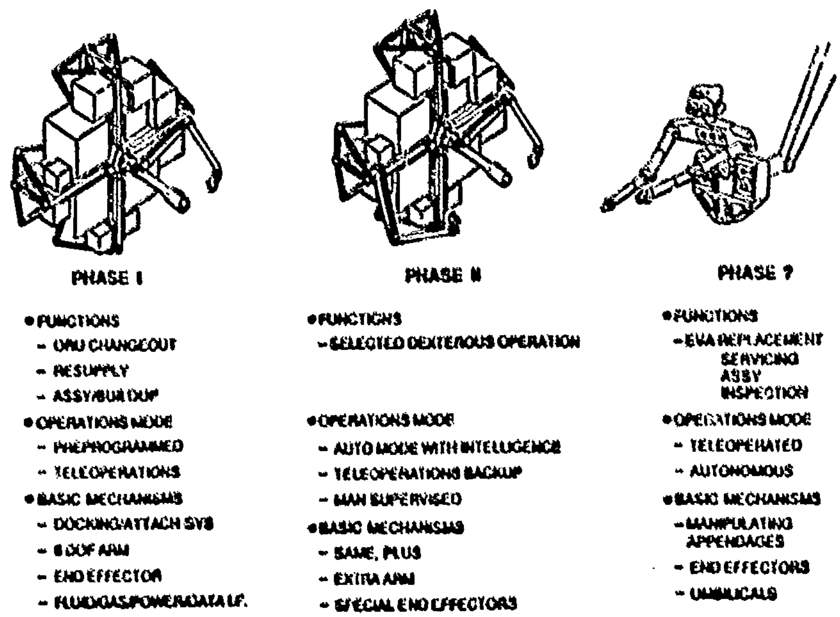

Figure 6. SFE Evolution

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INFLATABLE END EFFECTOR TOOLS

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ABSTRACT

Two types of inflatable end effector tools have been developed by OLIS Engineering to provide a compliant, controlled force grasping device for handling delicate composite structures or other items incapable of withstanding concentrated handling loads.

1.0 INTRODUCTION

Two variations of inflatable end effector tools have been developed by OLIS Engineering under a Phase II NASA SBIR contract. The primary purpose of developing this technology was to provide the capability of grasping delicate composite components for assembly of large structures in space. Several other benefits and applications of this system became apparent during the course of the development effort. The inflatable end effector tools utilize controlled air pressure to inflate a bladder of two distinctive configurations to provide the grasping force. Grasping forces can, therefore, be predetermined and set simply by controlling the maximum air pressure for that particular operation. Removal of the air pressure from the system deflates the bladder, releasing the item being grasped, and establishing a clearance situation for repositioning of the manipulator.

2.0 SYSTEM DESCRIPTION

The inflatable end effector tool system developed consists of two end effector tool assemblies (EETA-1 and EETA-2) and a pneumatic control unit (EETCU). The end effector tool assemblies are designed to interface directly with the standard end effector on the manipulator arm, and are controlled by a single pneumatic line to the pneumatic control unit.

In addition to the tool assemblies and control unit, a tool assembly storage module (TASM) is provided for storage of the tool assemblies when not in use. This unit permits access to the tool assemblies by the manipulator arm for special operations, while permitting use of the standard end effector when desired.

2.1 END EFFECTOR TOOL ASSEMBLY - TYPE 1 (EETA-1)

The EETA-1, as shown in Figure 1, consists of a central telescoping spine surrounded by an inflatable convoluted bladder. The forward end of the bladder is attached to the telescoping section of the central spine by a protective nose guard, and the aft end of the bladder is attached to the fixed section of the central spine by a clamp which also provides an air tight seal. Rotational stability is enhanced by support wires molded into the aft end of the bladder convolutions. The aft portion of the EETA-1 interfaces with the standard end effector on the manipulator arm. The EETA-1 shown in Figure 1 has been designed to interface with the end effector on the Proto-Flight Manipulator Arm at NASA-MSFC. The EETA-1 is designed to grasp items without specific handling points, and due to it's large inflation ratio, can handle a large range of tasks not previously feasible without task-specific end effectors.

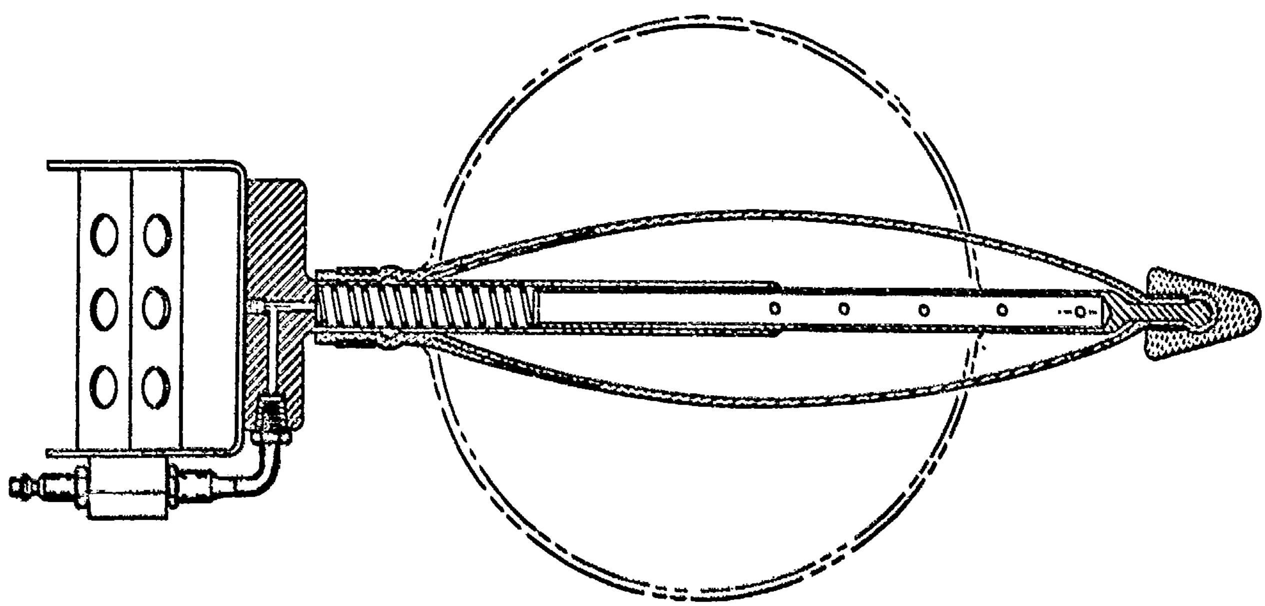

Figure 1. End Effector Tool Assembly - Type 1

2.2 END EFFECTOR TOOL ASSEMBLY - TYPE 2

The EETA-2, as shown in figure 2, consists of a fixed central spine surrounded by an inflatable bladder. The bladder is retained on the spine by a probe shaped bladder guard, which also serves to protect the bladder and assist in the insertion of the EETA-2 into a handling point. Compliant bumpers on the face of the tool assembly safely limit the insertion of the tool assembly into the handling point, and prevent damage to the item being handled. The aft portion of the EETA-2 interfaces with the standard end effector on the manipulator arm. The EETA-2 shown in Figure 1 has been designed to interface with the end effector on the Proto-Flight Manipulator Arm at NASA-MSFC. The EETA-2 is designed to grasp items with specific handling points, or items such as tubing or pipe where the EETA-2 can utilize existing deep holes as handling points.

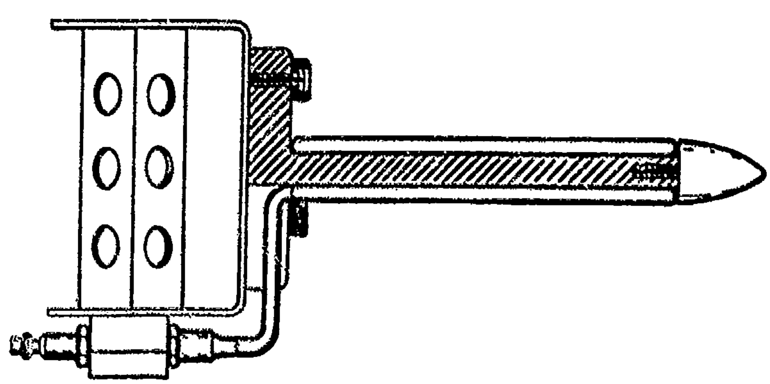

Figure 2. End Effector Tool Assembly - Type 2

2.3 END EFFECTOR TOOL CONTROL UNIT (EETCU)

The EETCU, as shown in Figure 3, provides either the EETA-1 or EETA-2 with controlled pneumatic pressure as specified by the operation to be performed. The EETCU is a manually operated unit, and was designed for development testing of the end effector tool assemblies at NASA-MSFC. While adequate for experimental and similar limited operations, more sophisticated control systems are contemplated for production operations. The EETCU, when supplied with standard shop air(125 PSI maximum) or dry Nitrogen, regulates the inflation pressure supplied to the end effector tool assemblies prior to inflation, inflates the end effector tool bladder to the preset pressure, and deflates the bladder when desired. In addition to shop air or dry Nitrogen, the EETCU requires 110 VAC power for operation of solenoid valves, switches, and status lights.

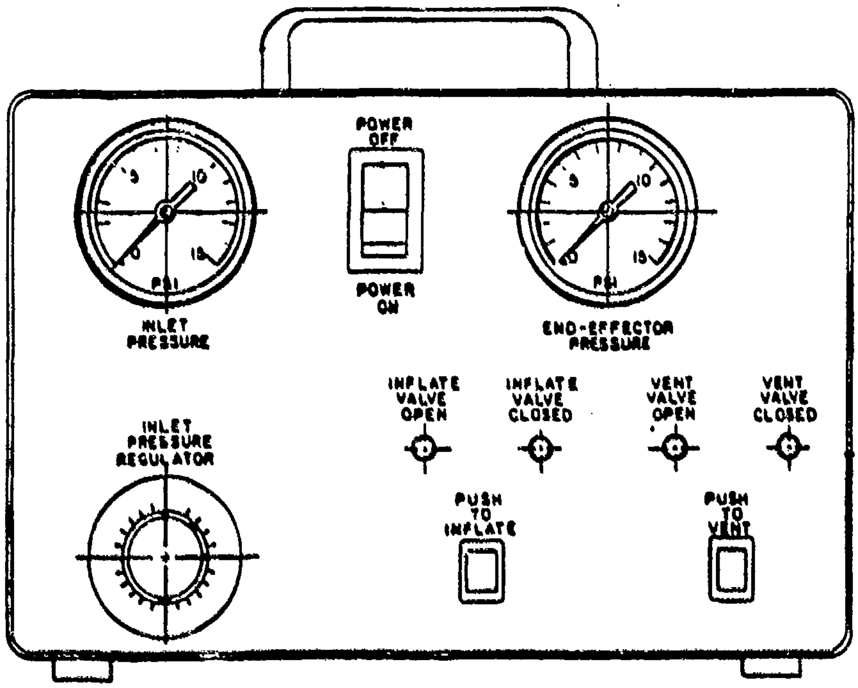

Figure 3. End Effector Tool Control Unit (EETCU)

2.4 TOOL ASSEMBLY STORAGE MODULE (TASM)

The TASM provides secure storage of the end effector tool assemblies when not in use and permits remote changeout of the tool assemblies as needed for specific tasks. The TASM consists of a sturdy base appropriate for the specific application supporting a storage module for each tool assembly. The tool assembly is inserted into the receptacle and turned clockwise to engage a latch. The manipulator arm end effector releases the tool assembly, and the pneumatic control line is disconnected at the quick disconnect fitting on the tool assembly. When needed again, the manipulator arm end effector grasps the interface on the tool assembly desired (this action also reconnects the pneumatic control line), turns counter-clockwise to disengage the latch, and removes the tool assembly from the TASM.

3.0 OPERATION

The operation of the EETA-1 and EETA-2 differs only in the handling point requirements. The EETA-1 can handle items by being placed in any convenient cavity within the range of the inflatable bladder, while the EETA-2 utilizes a deep hole of a specific size on the item to be handled which either has been provided specifically as a handling point or, by the nature of the part, already exists. An example of a typical operation using each type of tool assembly is described in the following sections.

3.1 EETA-1 TYPICAL OPERATION

Figure 4 shows the EETA-1 positioned within the substructure of a representative truss-type structural member. Once in this position, the bladder is inflated to a preset value previously determined to be safe for that structural member. Upon inflation, the bladder expands and grasps the structural member as shown in Figure 5. The structural member may then be positioned as desired by the manipulator arm. Disengagement is accomplished by simply venting the bladder. The spring internal to the telescoping spine extends the bladder longitudinally, providing considerable maneuvering clearance for retraction of the EETA-1 from the structural member.

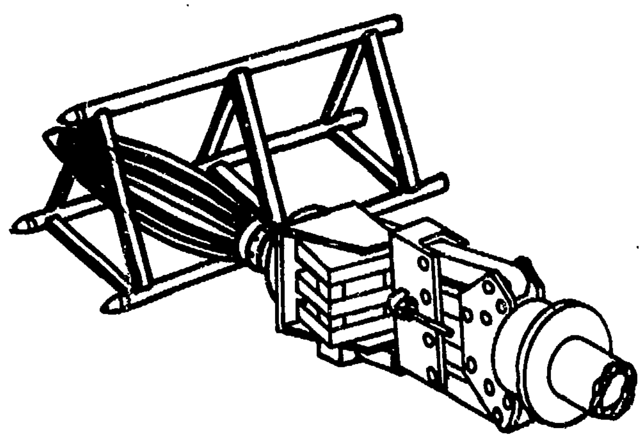

Figure 4. EETA-1 Positioned Within Structure Prior to Inflation

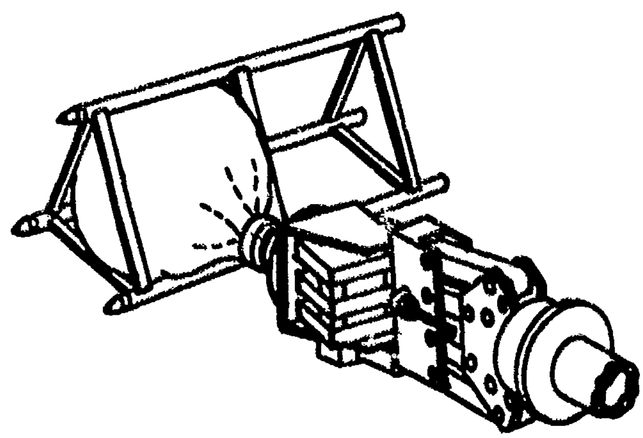

Figure 5. EETA-1 Inflated - Item Securely Grasped for Handling

3.2 EETA-2 TYPICAL OPERATION

Figure 6 shows a section view of the EETA-2 positioned within a hole provided on an item to be handled prior to inflation. Upon inflation of the bladder to a preset pressure previously determined to be safe for that item, the bladder expands and grasps the walls of the hole as shown in Figure 7. The item is grasped firmly by the EETA-2, and may be positioned as desired by the manipulator arm. The bumpers on the face of the EETA-2 prevent damage to the item being handled. Venting the bladder disengages it from the walls of the hole, creating a clearance situation for removal of the EETA-2.

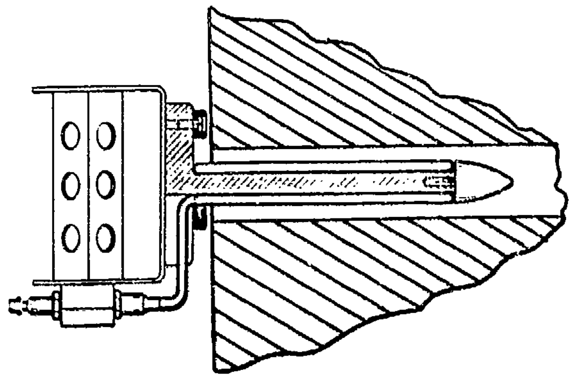

Figure 6. EETA-2 Positioned in Handling Point Prior to Inflation

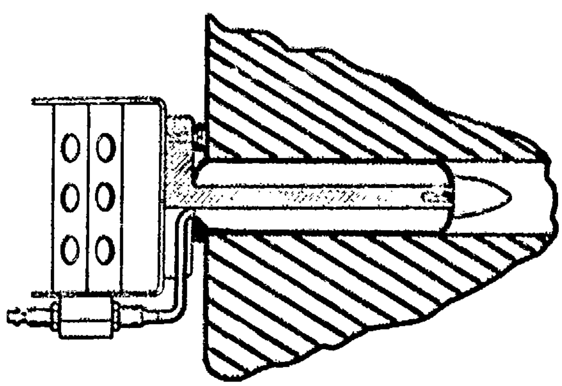

Figure 7. EETA-2 Inflated - Item Securely Grasped for Handling

4.0 ADVANTAGES/LIMITATIONS

4.1 ADVANTAGES

The inflatable end effector tool assembly system has several distinct advantages over other systems for certain specific applications. One of the more complex problems encountered in handling delicate parts (whether large or small) is preventing damage to the parts by applying excessive gripping force while still assuring that the part is being held securely for handling. Tactile sensors are extremely complex and costly, and point contact loads often exceed the allowable for a part before it is held securely enough for handling. The inflatable end effector tool assemblies can handle such parts with ease, as the grasping force is applied over a relatively large area with no concentrated loads applied to the part. The grasping force is 100% predictable, as it is applied directly by the pressure within the bladder, and is preset for the part to be handled prior to engagement.

Another advantage of the inflatable end effector tool assemblies over other systems is their inherent simplicity. EETA-1 has only one moving part and EETA-2 has no moving parts. When compared with more conventional end effectors, it becomes obvious that maintenance and Life Cycle Cost on this type of unit will be considerably less than for the mechanical grasping devices employed by most end effectors.

As the inflatable end effector tool assemblies are connected to the item being handled by a compliant bladder, a "buffer" or "shock absorbing" effect is automatically imparted to the system. It is anticipated that this feature will permit location of many parts simpler, as it allows for a small amount of flexibility in the system, enabling parts to locate on locator pins or similar locational devices with less positional accuracy requirements being placed on the manipulator system.

4.2 LIMITATIONS

As with all such devices, there are certain limitations of the end effector tool assemblies which must be addressed. The first and most obvious limitation is that the tool assemblies are at a distinct disadvantage when used to handle parts with sharp edges or protrusions which might cut or puncture the bladders. While a variety of bladder material may be specified for various applications, the handling of items with sharp edges or protrusions will seriously jeopardize the integrity of the bladders.

The inherent compliance of the system provided by the inflated bladders, while an advantage in some applications, may prove to be a limitation with respect to positional accuracy in other applications. Also, as there are no locational constraints on the tool assemblies with respect to rotation, the exact relationship between the manipulator arm and the rotational position of the item being handled is not fixed, and in some instances will cause problems in programming automated manipulator arm tasks.

Session V Program B

Manufacturing of Aerospace and Missile Systems I

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Keynote Speaker: R. E. Bowles
Chief of Mobility of Technology Planning and Management
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Presented at the Conference on Space and Military Applications of Automation and Robotics

21-22 June 1988 **GACIAC PR 88-02**

ROBOTIC ASSEMBLY OF MICROSCOPIC COMPONENTS IN MILLIMETER WAVE DEVICES

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ABSTRACT

The Automation Lab of Honeywell, Inc., Armament Systems Division, has developed a robotic system to perform delicate component assembly operations which are critical to the high volume production of millimeter wave sensors. This system was developed as part of a Manufacturing Methods and Technology Program which was funded by the U.S. Army Armament Research and Development Command (ARDEC).

The system consists of precision robotic devices which are guided by an integrated machine vision system to acquire, orient and solder gallium arsenide (GaAs) beam leaded components to a soft substrate. Assembly is accurate to within +/- .001 inch of a location defined by the microstrip artwork of a generic sensor circuit.

Component size is .008 inch wide by .025 inch long, including beam leads. A vacuum pick up tool was developed to manipulate the components. The tool does not touch the delicate GaAs chip during the operation, and does not apply over three grams of force to the component at any time. The components are held in position on the substrate by the tool while they are bonded to the substrate by an integrated laser soldering system.

INTRODUCTION

A major barrier to economical implementation of sophisticated weapon systems are the labor intensive production techniques used to produce the complex system sub-assemblies.

Target seeking munitions, such as SADARM, may employ millimeter wave sensors to locate and identify potential targets. Due to the high frequency operation of the MMW circuitry, a sensor designed with discreet components requires the use of microscopic GaAs diodes. These diodes are extremely fragile and difficult to manipulate. In addition, the diodes must be soldered to the sensor microstrip with an extremely high degree of accuracy (typically +/- .001 inch) with respect to the circuit artwork.

In the best scenario, where economical assembly is the goal, these components would be bonded to a ceramic substrate using thermal compression bonding. When producing large volumes of sensors, however, PTFE laminated substrates offer certain advantages over ceramic. Unfortunately, due to the softness of this material, thermal compression bonding will result in small depressions in the microstrip. Millimeter wave experts are divided in opinion on the effect these depressions have on the performance of the sensor. It has been specified for this project that the GaAs components be soldered to the circuit. Hand soldering these components is a tedious procedure, which must be performed by a skilled operator using a high power microscope. This method is prone to high reject rates and damage of very expensive components.

Major technical advancements were necessary to make the high volume production of millimeter wave sensors economically feasible . As part of a Manufacturing Methods and Technology Program, sponsored by ARDEC, these major producibility problems were investigated, with the ultimate goal of building an automatic system to perform the assembly task.

APPROACH

The approach to the task of assembling the sensors was to make use of robotics and machine vision for component handling, and laser technology for component bonding.

The precision required for the assembly demands a system which can correct for inaccuracies which are inherent in any mechanical system. A system comprised of a servo-driven robot arm guided by machine vision is simply the only approach currently available. These systems also have an advantage in that they are flexible and can be converted to other programs or assembly tasks for a minimal investment.

A soldering technique using a laser was envisioned to bond the components to the substrate. Using this technique, heat could be applied to the solder joint with pin point accuracy and extreme consistency, without requiring mechanical contact of a heated tool.

A flexible work cell was conceptualized which would make use of these basic concepts. The work cell (Figure 1) was constructed from purchased robotic and laser components, and special purpose tooling developed by Honeywell's ASD Automation Lab.

SYSTEM CONCEPT

The sensor housing, containing the circuit substrate, is fixtured on a three axis servo driven staging unit. This stage has positional resolution of .5 micron (.00002 inch) and is guided by machine vision. The diodes are manipulated by a four axis Cartesian robot, also guided by machine vision. The function of the staging unit is to precisely manipulate the circuit, using it's machine vision, in a manner that will compensate or the position of the circuit artwork with respect to the stage. It also compensates for small errors during diode acquisition by the robot. The robot selected was proven, through rigorous testing, to have a positional repeatability of +/-5 micron (+/-.0002 inch) over a several hour time span. The stage and robot work interactively to bring the circuit and diode together in a precisely mated position. This position is chosen to coincide with a stationary laser beam, which is used to solder the diode to the circuit.

The general idea is to make use of two facts. Pre-determined robot positions can serve as location datums, since the robot's capability to return to these positions is known to be excellent. Secondly, the stage's extremely high resolution makes negligible the error in stage motion with respect to the robot location datums. The result is that the assembly accuracy of the system is limited, for all practical purposes, only by the the robot repeatability, and the camera and pixel resolution the machine vision system. As an added benefit, the Cartesian robot's large work envelope and high speed give the system flexibility to be used for applications in which a large variety of components must be assembled.

Considerable effort was spent in the investigation and testing of commercially available robotic equipment for use in this system. Ultimately, an integrated package consisting of a robot, stage,and machine vision system was purchased from Accusembler Robotic Systems. This system was chosen over several competing systems for two reasons. First, tests showed that a Cartesian configuration of ball screw actuators is inherently the most repeatable multi-axis system available. The Accusembler Cartesian robot has a work envelope which is several times as large as the competitive systems'. Secondly, Accusembler offered a package which was integrated completely from Accusembler components. The system could therefore be programmed using a single language, greatly reducing the custom software requirement.

Our experience was that the Accusembler Cartesian robot and stage were extremely reliable, accurate machines. However, the binary vision systems used were not the best suited for the application. Since the analysis of the circuit artwork is performed by detecting edges, a system employing grey-scale rulers would be much faster and better suited for the vision processing tasks.

Even so, during extended operation, the system consistently performed the assembly per the stated accuracy requirement. During the final demonstration for ARDEC, the system successfully assembled 120 diodes without failure. Although a minor calibration error shifted the mean of the sample slightly, all 120 samples were grouped in a range covering ± .001 inch.

The authors wish to thank the Accusembler applications specialists, whose technical support greatly contributed to the success of the project.

SYSTEM OPERATION

Vacuum release trays containing diodes are placed on specially designed back-lighted pedestals. A camera on the tooling axis of the robot locates individual diodes on the trays. This information is used to direct the robot to position the vacuum pick up tool over the diode. The diode is then removed from the tray with the tool and transported over the first stage controlled camera (Figure 2). The robot position at this point serves as the first location datum. The camera determines the exact offset of the diode from the center of the vacuum tool (Figure 3).

Next, the stage, containing the circuit, is driven beneath a second stage controlled camera. This camera's function is to determine the location of the set down point on the circuit artwork. Information provided by both cameras is used to calculate the offset motion required by the stage to compensate for all deviations in circuit artwork and diode acquisition positions on the vacuum tool. The stage then moves to this offset position.

With the circuit now brought into position by the stage, the robot moves to a second datum location. This robot position is established so that a diode which is perfectly centered in the vacuum tool will be perfectly located with respect to a stationary laser beam. The stage has previously adjusted for any offset between the diode and vacuum tool. Consequently, the diode is now held perfectly in position on the circuit artwork. If the offset between the diode and vacuum tool is not too great, the laser beam will hit the bonding site close enough to the ideal spot to generate a good solder joint (Figure 4, 5).

An Nd:YAG laser, supplied by Control Laser Corporation, whose beam is transmitted through a path of beam benders to the bonding site, solders one lead of the diode to the circuit.

After the first diode lead has been bonded, the robot releases the diode and raises slightly above the substrate. Both the robot and the stage then shift so that the opposite bonding site is positioned under the laser, and the robot lowers to hold the opposite diode lead down. Then, the second diode lead is soldered. Upon completion, the robot goes back to find the next diode on the tray and the stage positions the next bond site under the substrate measurement camera.

The process of acquiring, positioning and bonding one diode requires 30 seconds. After several diodes have been soldered in place, the housing is removed from the fixture.

DEVELOPING THE PROCESS

A number of problems were addressed in the development of the diode handling and soldering process.

A suitable method was needed to transport the diodes from the diode supplier to the work station. We experimented with Vichem Corporation's Gel-Pak vacuum-release chip carrier and shipping system. The Gel Pak design addresses the problems of maintaining diode location during shipping and diode removal. The part trays are covered with a tacky film and have a vacuum-release feature which allows parts to be released on demand. To facilitate removal of a diode, a vacuum is applied to the under surface of the Gel Pak. The film is drawn down over a silk screen within the pak. This action reduces the surface tension of the diode to the film and permits the removal of the diodes by the robot vacuum tool. We found that beamlead diodes (even those with weak lead strength) could be safely picked up and transferred from one Gel-Pak to another.

A major effort was directed towards the task of choosing a solder and applying it to the substrate for the purpose of bonding the diodes.

The solder used in this process is indium based. Indium based solders are good for applications involving gold. This is because indium drastically reduces gold "leaching", or the absorption of gold atoms into the solder matrix. Leaching is a characteristic of tin based solders, which are commonly used in most electronic circuits. The indium alloy selected is commonly used for the soldering of heat sensitive components, since it has a low reflow temperature.

Solder must be applied and reflowed very accurately to create solid solder "pads", which are adequately registered on the circuit artwork. A screen printing method is well suited to this application. With this technique, solder paste is squeezed through a screen, or stencil, which has been fabricated with openings located in the solder pattern required for the diodes. This process requires an appropriately designed substrate/housing assembly to allow the screen to be positioned directly on the substrate surface.

Once the correct amount of solder has been applied, the substrate is run through a vapor phase operation to reflow the solder into the solid pads.

To promote wetting of the solder to the component, the solder bumps must be refluxed. Due to problems associated with rosin fluxes, synthetic fluxes were investigated. A particular type of synthetic flux, Multicore X-32 has several highly desirable properties. X-32 is essentially invisible after application, therefore, it does not interfere with machine vision analysis. Also, X-32 has a solid content of only three percent. Any necessary cleaning can be performed using standard cleaning processes and equipment. Vigorous rinsing is not required.

Finally, we needed to develop a means for the robot to handle the delicate GaAs components. The diodes must be acquired from the gel-pak and placed on the substrate without any diode damage. To accomplish this, a vacuum pick up tool was designed to hold the diode in a way that the diode chip is contained in the vacuum hole. The diode leads, meanwhile act as "keepers" to prevent the entire diode from being swallowed by the tool. In this way, no mechanical load is ever placed directly on the GaAs chip (Figure 6). The tool is made of a stack of thin metal sections, giving it extremely low mass. When holding the diode to the circuit, a load of about 2 grams is applied to the diode beam leads. This blade-like design allows the laser to bond either diode lead by simply shifting the robot and stage a small amount, instead of rotating the assembly 180 degrees (Figure 7).

CONCLUSION

The results of this project have shown that microscopic beamlead components can be acquired and bonded accurately to flexible substrate material using automated methods. To be sure, improvements can be made to the system developed for this project, but the feasibility and practicality of this type of assembly has been proven. Systems such as this have a definite place in the manufacture and assembly of millimeter wave devices which utilize these microscopic components. Indeed equipment such as this could probably be adapted to many tasks requiring microscopic parts handling and assembly.

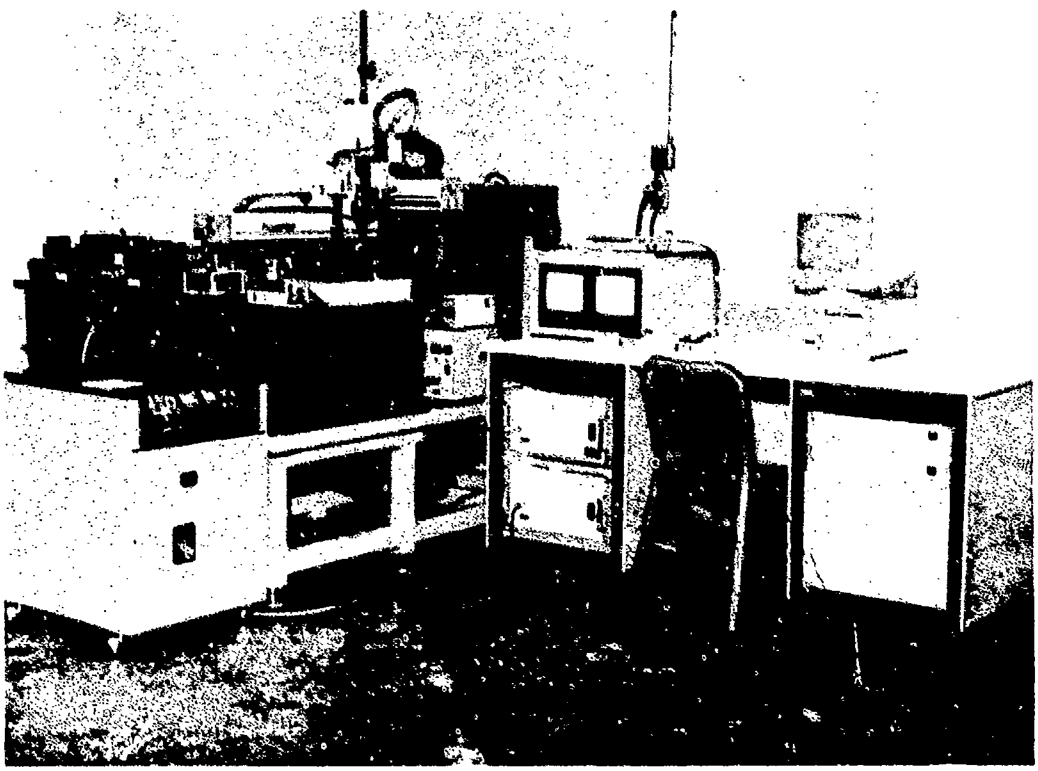

Figure 1

Flexible Work Cell for Microscopic Component Assembly
Developed by Honeywell ASD Automation Lab.

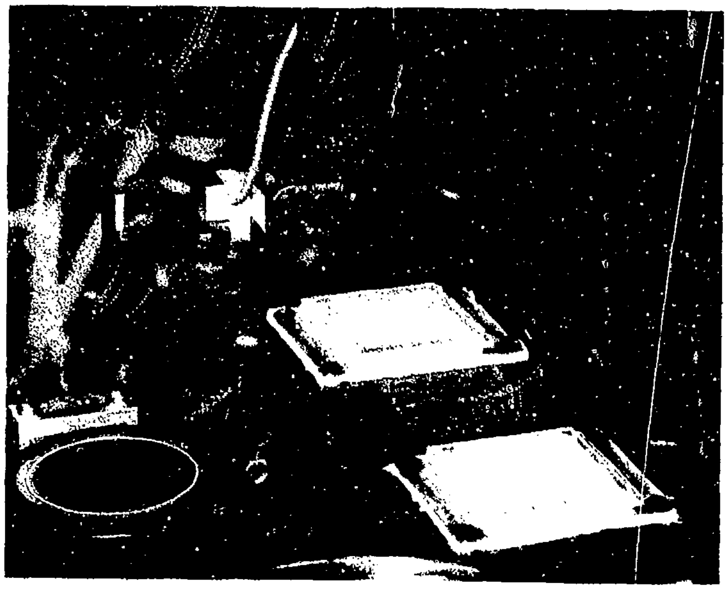

Figure 2

Robot tool holds diode over camera.

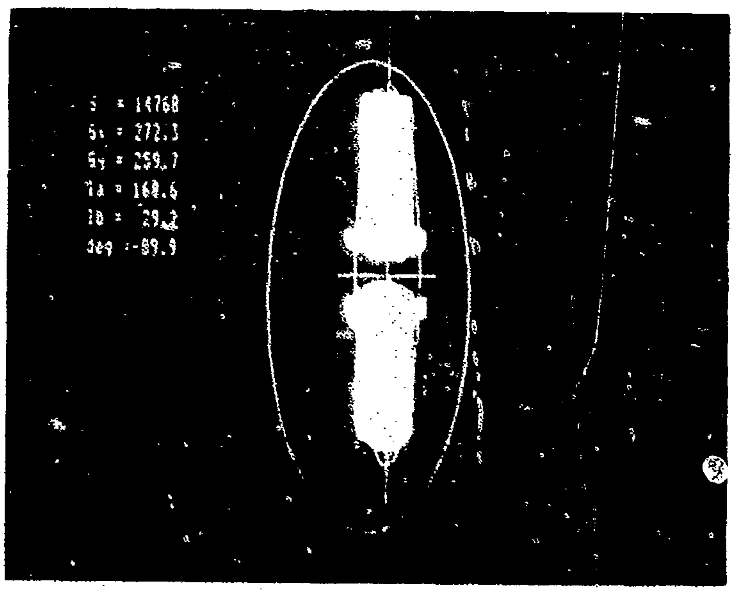

Figure 3

Machine Vision determines offset between diode and robot axis.

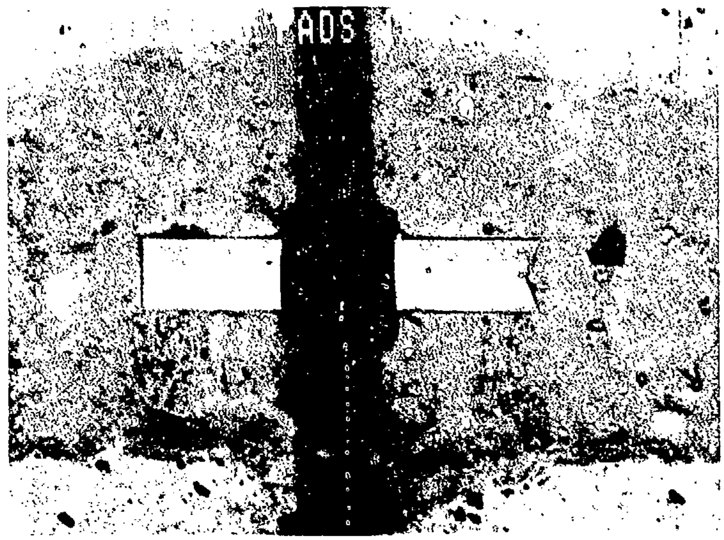

Figure 4

SEM photo of diode soldered to circuit.

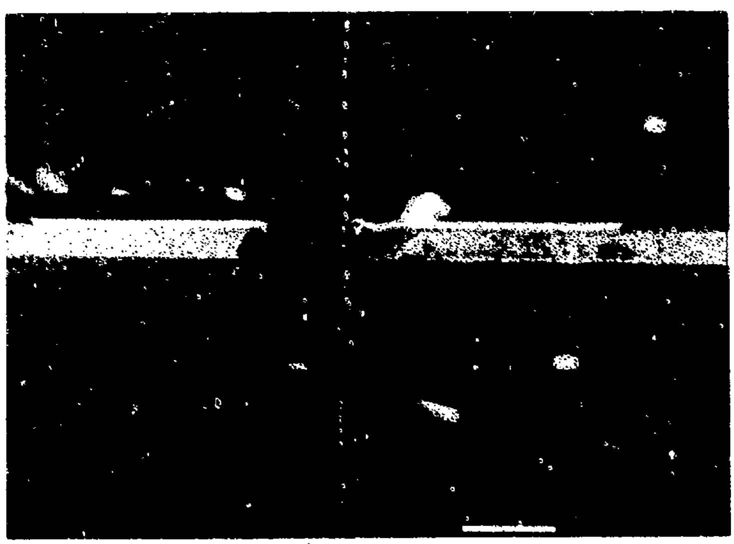

Figure 5

SEM photo of cross section showing solder - lead interface.

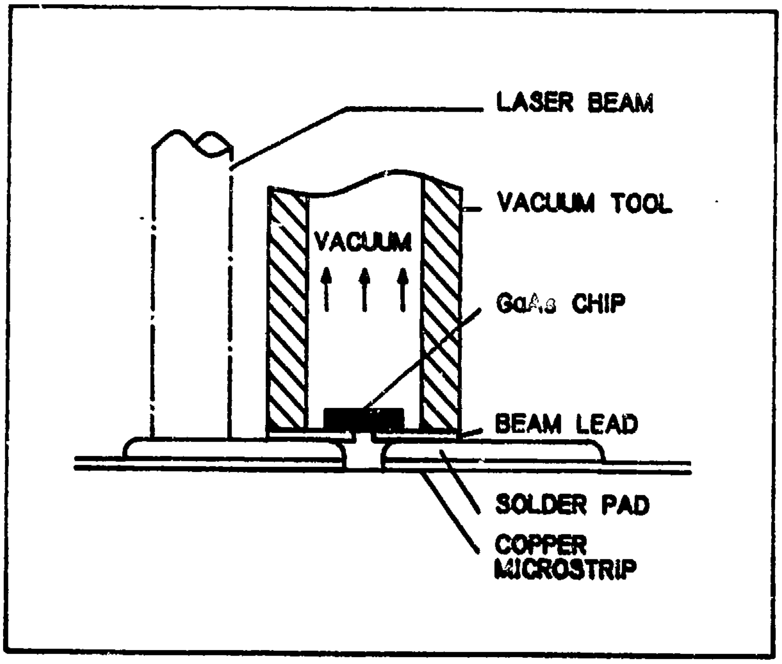

Figure 6

Vacuum tool holds diode without touching chip. Hold-down force is applied to leads during solder reflow.

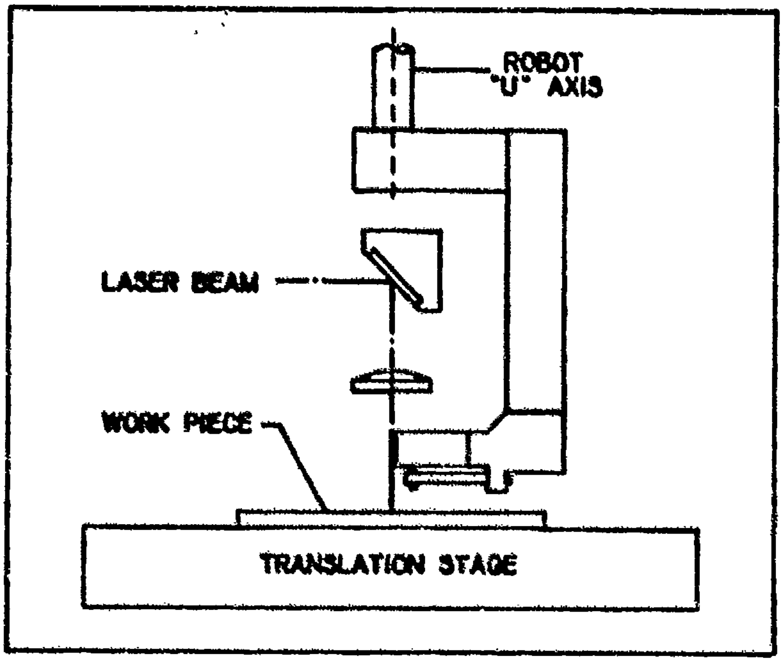

Figure 7

Tool is designed to accomodate laser optics.

Presented at the Conference on Space and Military Applications of Automation and Robotics

21-22 June 1988 GACIAC PR 88-02

AUTOMATED MILLIMETER WAVE (MMW) TRANSDUCER TESTING IN A ROBOTIC/VISION TEST CELL

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ABSTRACT

This paper addresses the issues associated with testing Ka-Band Millimeter Wave (MMW) Transducers in high volume production. The issues include 1) tuning/testing the MMW transducer by trimming a conductor pad, 2) testing for RF parameters and programming a PROM with transducer specific information, and 3) interfacing all elements of the test cell through the use of robotics.

INTRODUCTION

Honeywell has carried out a Manufacturing Methods and Technology (MM&T) Program* that has addressed the above issues and transitioned the testing of MMW transducers from the lab into high volume production using robotics, lasers, and state of the art test techniques.

The MMW transducer represents the front end of a MMW radar system. The transducer includes a transceiver (transmitter and receiver) and a MMW planar antenna. The transceiver consists of a component populated substrate nested inside of a metal housing. The antenna is soldered to a metal wedge located beneath the housing. The transducer described above is generic by design and was used specifically for this program.

The standard approach used in tuning and testing this type of device is very labor intensive. A skilled technician performs the tuning operation by hand-cutting a conductor pad using a scalpel while observing the operation under a microscope. The adjusted frequency is then measured. If the target frequency is not reached, subsequent trim/measure operation(s) are required. The test process involves manually connecting the power supply and signal lines, positioning the device for proper antenna beam pointing, setting up different test instruments, and manually recording information from each instrument. The entire manual tune/test process requires 6-8 hours of a technician's time.

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* Contract DAAA21-85-C-0320 Millimeter Wave Manufacturing Methods and Technology Program, U.S. Army AMCCOM Armament Research Development and Engineering Center.

TEST STATION

The simplified block diagram of the test station is shown in Figure 1. Three separate work stations surround one robotic's parts handler. The work stations include (1) a laser trim/frequency tune station, (2) a radio frequency (RF) test cell, and (3) a programmable read only memory (PROM) programmer cell. Overall control and monitor of operations is provided by two Intel series 310 computers. The robotic part handler performs load and unload operations on both the transducer and a PROM. The robotic end effector is shown in Figure 2. The end effector includes two pneumatically controlled grippers used for pick and place of the transducer parts. It also includes a vacuum type pickup tool for the PROM package. Operations of the three work stations are performed simultaneously. Special part fixtures which automatically make connections and place a simulated transceiver cover on the transducer housing prior to testing are located at the laser trim and RF test work stations. These fixtures have an opening which allows the MMW antenna to transmit into a small anechoic chamber. A scaler horn lens is positioned at the opposite end of each chamber for the purpose of RF measurements. For simple frequency testing (trim station), measurements may be made in the near field. However, the RF test station must have a far field antenna chamber.

PROCESS DESCRIPTION

The first step in the process is robotic pickup of the transducer. The part is scanned past a bar-code reader for serial number identification.

The next operation performed is a laser trim/frequency tune. Figure 3 shows the laser trim system internal parts handling concept. Once the part is placed into the fixture and the proper power supply voltages are applied, the transmitted center frequency is measured. Based upon the frequency data, the computer determines the amount of metal conductor which must be removed from the resonator pad of the transmitter circuit in order to reach the desired center frequency. The laser trim system includes simple pattern recognition (nondestructive edge sense) which is used to find the location of the conductor pad to be trimmed. The laser used for this process is nd:YAG thick film system. The effective width of the conductor pad is reduced symmetrically. This transceiver was designed such that it always operates at a frequency lower than the specified center frequency. Once the pad has been trimmed, the transmitted frequency is rechecked. If the frequency has not reached the center frequency specification, up to two more fine tuning (trim) operations will be performed. This iterative process requires a maximum of 20 seconds.

Once the transducer has been properly tuned, it is robotically removed from the laser trim fixture and placed into the RF test fixture. The RF test fixture (Figure 4) is controlled by pneumatic cylinders which are switched by the robot's I/O lines. The fixture accepts a transducer from the robot such that the antenna is pointing downward. The fixture then makes the required electrical connections, press fits a metal cover over the part, and repositions the part so that the antenna transmits horizontally into the RF test antenna chamber. At the RF test station, a series of five tests are performed: (1) output power, (2) Voltage Controlled Oscillator (VCO) weep characterization, (3) VCO linearity, (4) RF to IF gain/bandwith, and

(5) noise figure. Test data is transferred from individual RF equipment to the station computer over the IEEE 488 Bus. Total RF test time can take as long as 85 seconds.

Once a transducer has passed all tests, a PROM package is robotically picked up from a component feed fixture and placed into a PROM programmer socket. The PROM is programmed with the transducer specific data obtained during VCO sweep characterization. It is then picked up by the robot and sent along the production line with its paired transducer.

Since the three work cells operate simultaneously, the overall rate of transducer testing is the sum of the RF test time (longest work cell time) plus one load and one unload operation. The average test time demonstrated thus far has been under 95 seconds per transducer. Process improvements can reduce this test time further. Figure 5 includes a summary of rates. The overall Mean Time Between Failure (MTBF) for the station is 772 hours.

CONCLUSION

The equipment built is generic rather than product specific so that it can be easily modified to process several different types of MMW transducers. Since tuning and testing techniques are very common from one product to the next, the bulk of the equipment is reuseable. The major effort involved in station changeover would be the fabrication of new tooling (i.e., part holding fixtures, robotic and effectors, connectors, etc.). In an effort to transition this type of product into high volume production, several assembly/test process improvements have been implemented and others have been planned.

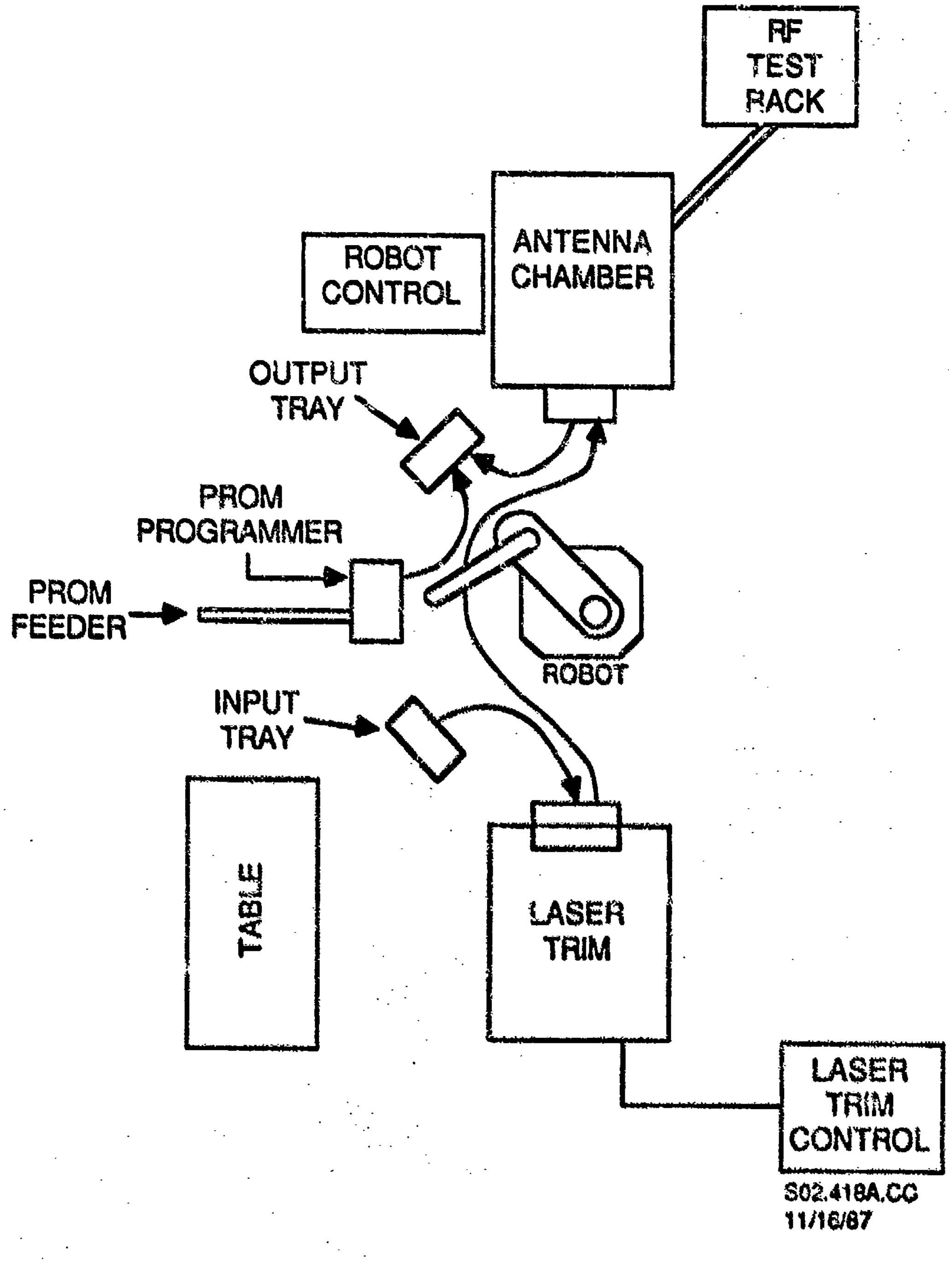

FIGURE 1.
OVERHEAD VIEW OF TUNE/TEST STATION

Honeywell

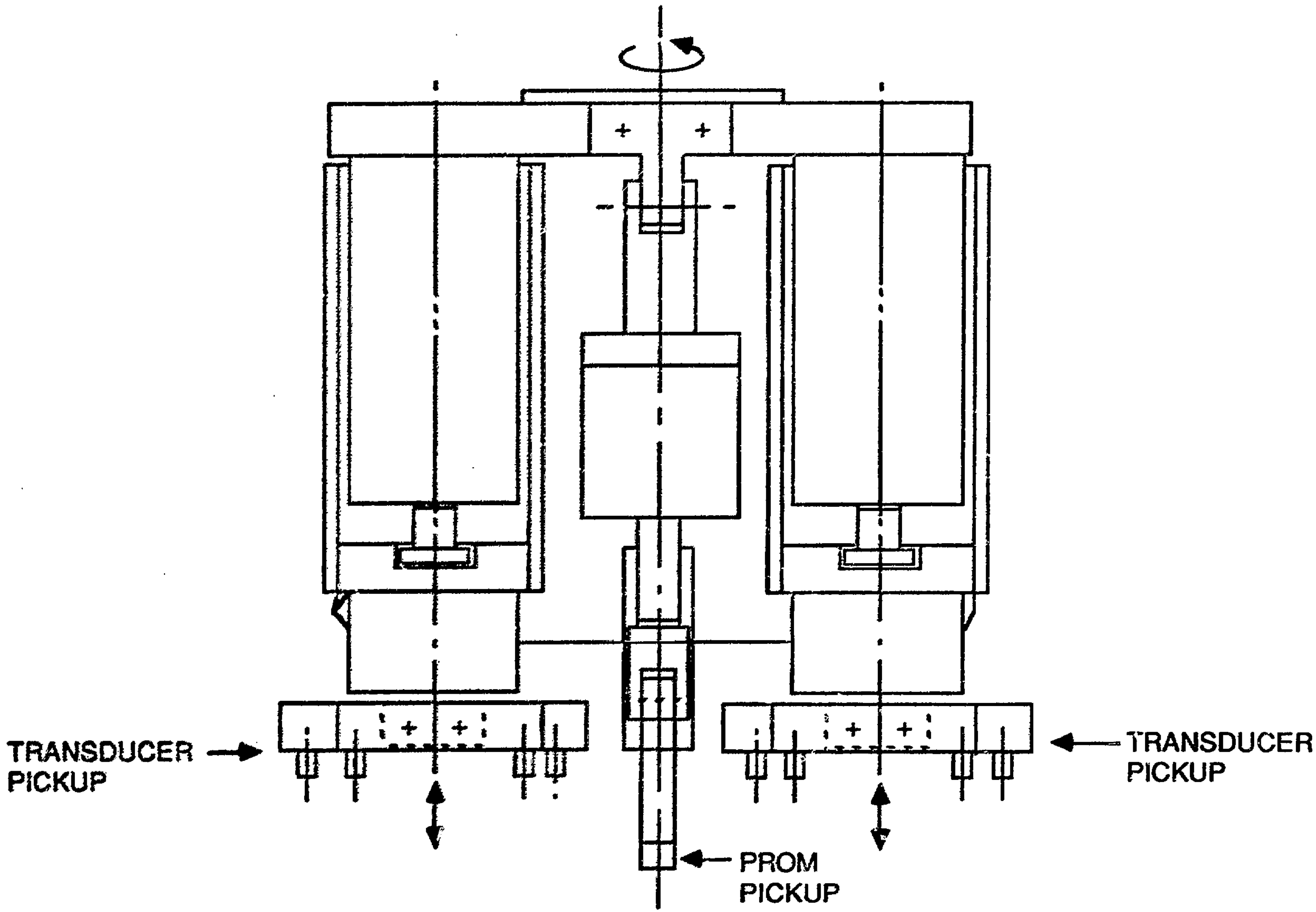

FIGURE 2. ROBOT END EFFECTOR

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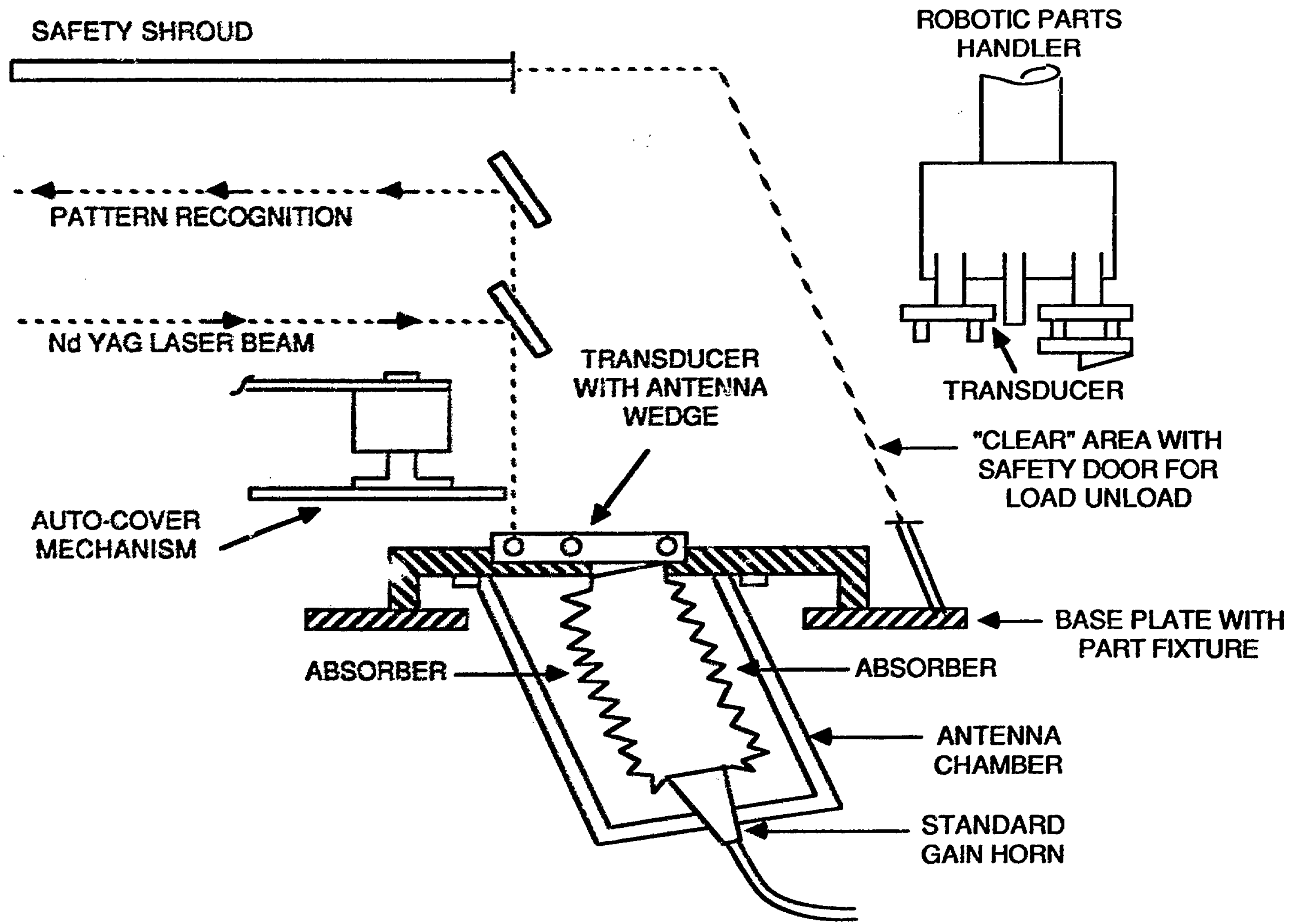

FIGURE 3. INTERNAL TRIM AND PART HANDLING CONCEPT

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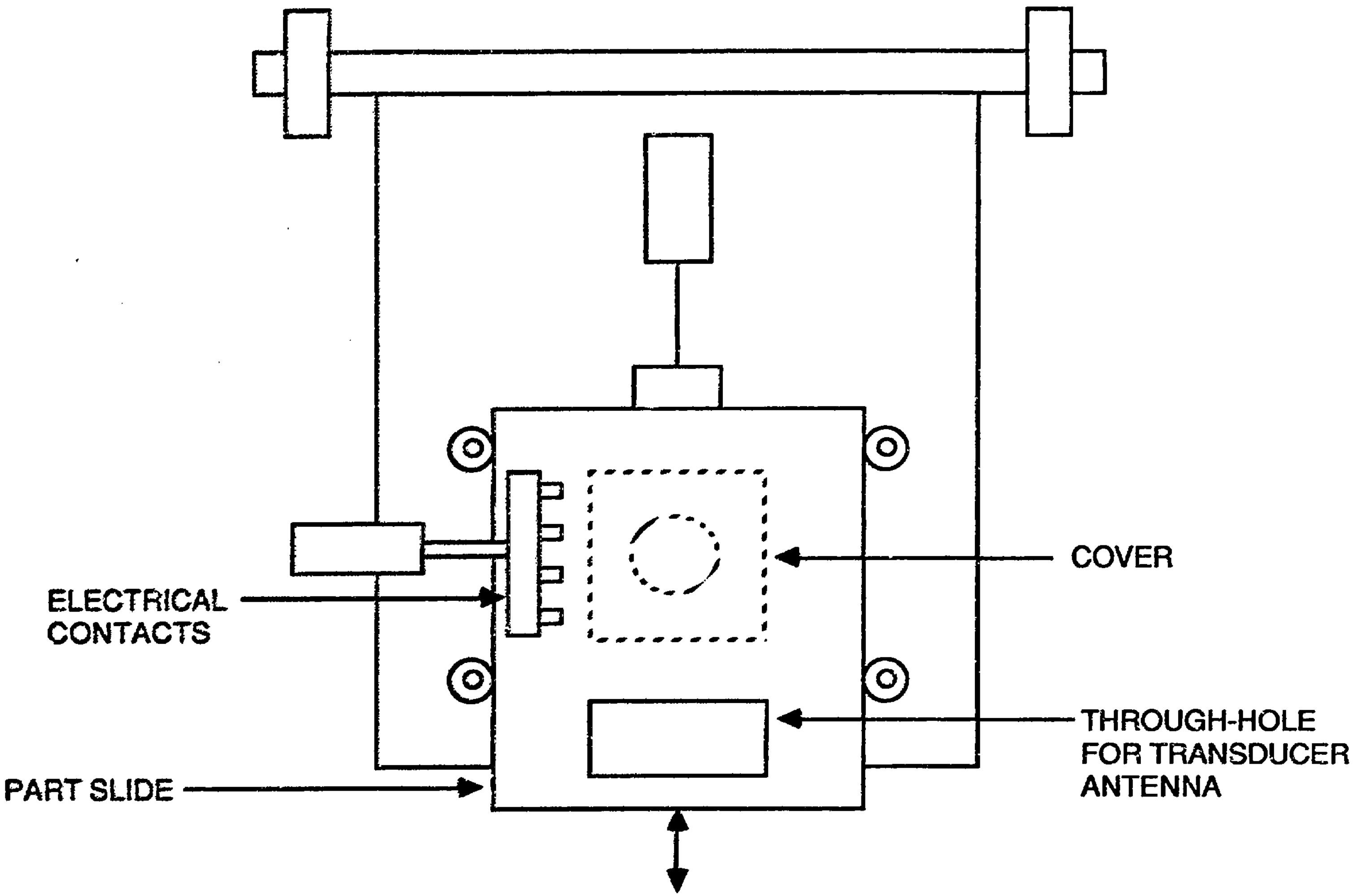

FIGURE 4
RF TEST FIXTURE

DEFENSE SYSTEMS GROUP

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	OPERATION	TIME (SEC)
A.	CENTER FREQUENCY ADJUSTMENT (MAXIMUM TIME)	20
B.	RF TESTING (MAXIMUM TIME)	85
C.	PROGRAM PROM	2
D.	UNLOAD AND LOAD OPERATION TRANSFER FROM TRAY TO FIXTURE, FIXTURE TO FIXTURE, ETC.	10

OVERALL RATE OF STATION = B+ D = 95 SEC

FIGURE 5. SUMMARY OF TEST STATION RATES

DEFENSE SYSTEMS GROUP

Presented at the Conference on Space and Military Applications of Automation and Robotics

21-22 June 1988 **GACIAC PR 88-02**

DEVELOPMENT OF AN INTEGRATED CAD/CAM SYSTEM FOR WIRE HARNESS FABRICATION

June 1988

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ABSTRACT

This paper describes the development of an integrated CAD/CAM system for wire harness fabrication. The computer integrated Manufacturing (CIM) system is based upon a desktop AutoCad Computer Aided Design workstation and MICOM's Robotized Wire Harness Assembly system (RWHAS). The CIM system extracts and processes information from a Computer Aided wire harness Design file to generate the input file for the RWHAS Executive Controller. The data is transferred to the RWHAS CAM system via an RS-232 interface. The RWHAS then manufactures the harness.

INTRODUCTION

In this paper we will be discussing the ideology, the research, and the development of a true integrated CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing) system. The concept of a CIM (Computer Integrated Manufacturing) system is not new and the development of such a system is not yet a defined science. When research began on this project it was our intent to create a system where design could take place on a micro computer and automatically be loaded, by means of a VAX, to a fully automated wire harness manufacturing system. It should be noted here that although we are speaking of the electrical wire harness fabrication for use in missiles it is not confined to the weapons industry. This technology has far reaching impacts into other industries as well. For example, this technology can be applied to the construction of automobiles, airplanes, ships, etc. This wire harness in its completed form will be composed of a group of wires tied together with ends inserted into the appropriate connectors for the missile. The wire ends that will not be used in one of these connectors will be prepared with suitable fittings to be used as separate connections. We used a microstation CAD package called AUTOCAD to do all the design work in our system. The CAM system we are using is called RWHAS (Robotized Wire Harness Assembly System). The principle robot that is used for RWHAS is an IBM 7565. We have configured this robot for wire harness fabrication. The robot operates on a formboard table that is calibrated so that the robot will know where each connector, gate, breakout, etc. is located. A more detailed description of RWHAS and its components along with AUTOCAD will be given later. See Figure 1 for flow chart of system operation.

THE CAD SYSTEM:

We have elected to use the design package AUTOCAD on a personal computer (PC) to achieve the CAD portion of this project. AUTOCAD seems to be more versatile than the other leading microsystem CAD packages for this application and it also offers the added dimension of an embedded programming language called AUTOLISP. AUTOLISP is a derivative of the popular programing language LISP, used to handle lists of characters, words or strings.

The first step to designing a CAD/CAM system was to build our database for the wire harnesses we would be fabricating. This database was constructed on the PC using AUTOCAD. Each wire harness requires the use of several different components. The first components added to the database were the "connectors", with corresponding pin insert configuration, used to connect the wire harness to the missile subsystems. The wires, with pins attached to the ends, are inserted into the connector pin holes. Our next entry into the database was the various "gates" used in the manufacturing process. Like the connectors, there are several types of gates used. The primary purpose of these gates is to hold the wires up off the table while fabrication is taking place. These gates are also used in the software to determine the start, end, or continuation of "routes." Routes are defined as the paths wires can take when going from one component to another. Another component included in the data package is "breakouts."' Breakouts are used at the beginning or end of wires. These starting or terminating devices serve to hold the wire ends that are not prepared for connectors. The final component added to the database was "ties." Ties are used to tie the wires together after the wire harness is complete. All of these components were created as "blocks" so the user could bring them into the drawing and place them in the design as one entity. The term "block" comes from AUTOCAD and defines an object composed of several entities identified as one entity.

There is a separate database created by AUTOCAD as the design is performed. This database contains the individual information about each "block" such as scale, rotation angle, insertion point, etc. This information proved to be very useful for using LISP programming to place the routes and write the "From-to" statements. The from-to statements will carry information about each of the wires that make up the harness.

The next step was the development of some user interface facilities. We are presently making use of several utilities offered by AUTOCAD such as predefined commands assigned to the mouse. We used AUTOCAD to create customized menus which included all the components in the wire harness database which are needed to run RWHAS. With the use of these customized menus, we have been able to make help screens available as a menu choice. The menu also provides load and run options for the LISP programs embedded in the design package. Any AUTOCAD command can be used in conjunction with the specialized menus that were created including commands such as EDIT, ZOOM, etc.

Probably the most desirable feature of the AUTOCAD software is the ability to write and use somewhat complex programs using AUTOLISP. The programing language AUTOLISP is a very flexible and very versatile language. It combines the list processing ability of LISP with the commands used in AUTOCAD as well as DOS. There were two very complex programs needed in our wire harness design package. One program is to place the routes mentioned earlier and one to accept "from-to" statements and write all the information to a file that could be accessed and manipulated by the VAX. The routes, as stated earlier, are the paths the wires can take. When placing these routes the user need only pick the components with the cursor. The paths will then be drawn and written to the data file automatically. The From-To statements, on the other hand, are detailed descriptions of the wires used in the wire harness. The program created for From-To statements will prompt the user for the necessary information about the wires such as wire type and gauge. The attributes and data contained in the drawing are extracted and written to the data file by a LISP program and the AUTOCAD command ATTEXT (attribute extract). The help screens are also created through the use of a LISP program.

AUTOCAD EXTRACTION:

The extraction of design data from AUTOCAD has been simplified to a large extent by use of a command called ATTEXT (attribute extract). This command automatically extracts data requested from a drawing file and writes it to a storage file. The format and content of this storage file will be dictated by a template file that must be created by the programmer. This template file is a list of commands telling

AUTOCAD what data to send to the storage file and in what format it should be. In our particular design we are only concerned with the blocks when using ATTEXT. The block name along with the component number, the rotation angle, and insertion point is required. A file called RWHAS.TXT was designated as our storage file. After all necessary data from the blocks has been written to the RWHAS.TXT file, the file can be appended very easily for the addition of information from the routes and from-to statements. ATTEXT must be executed before any other appending of the storage file takes place because ATTEXT is set up to write a file, not append a file. Therefore, data contained in the storage file is overwritten when ATTEXT is executed.

THE ROBOTIZED WIRE HARNESS ASSEMBLY SYSTEM

(RWHAS)

RWHAS Operations:

RWHAS is composed of several different subsystems. Each subsystem has its own manager. The following is a list of different subsystem workcells contained in RWHAS:

System Controller

Wire Preparation Cell

Wire Reeling Cell

Wire Termination Cell

Wire Queuing Cell

Wire Layup Cell.

RWHAS utilizes off the shelf equipment involving several different operating systems. All equipment interfaces with the system manager and are tied together through a multibus.

Input File Characteristics:

A data generator program, which is written in ADA programming language, resides on a Digital Electronic Corporation's VAX 11/750 computer. The input file for the data generator contains the necessary data to run RWHAS such as type of connectors, wires, and fixtures needed for the harness fabrication. The x and y coordinate locations for all the components used will appear in the input file.

The data generator uses the input file to create various harness data files which will be sent to the different work cells of RWHAS. These files will contain lengths of wires needed, types of termination, and lists of connectors and fixture locations needed for fabrication. The files which are created by the data generator are then downloaded to a system controller which will send the necessary information to the work cells and monitor the system for errors.

Major Components of RWHAS:

The system controller is an Intel 86/30. Data files created by the data generator on the VAX are downloaded to the Intel. The system controller acts as the RWHAS System Manager and sends out wire harness data to the various work cells. The system controller will also monitor the system and keep track of where each wire is in the fabrication process and if any errors have occurred.

The wire marking device which is used in RWHAS is a Westland Laser Wire Marker (See Figure 2). The Westland is controlled by a Digital Micro PDP-11 computer. The laser marker receives a wire list file from the system controller. The wire list file will contain the lengths of the wire required for the harness and how they are to be marked. The laser marker will choose the wire from sixteen different spools and cut and mark them. Once the wire is marked and cut, the laser marker will feed the wire into canisters which are on the wire reeling work cell. All errors occurring on the Laser Marker will appear on the terminal for the wire preparation supervisor.

The wire reeling table is a circular table which holds three wire canisters during operation (See Figure 3). The reeling table prepares the canisters for pick-up by the termination robot. The table reels the cut wire into the canisters and leaves approximately two inches of wire extending from the canister chucks. The reeling table is monitored by the system controller and any errors will be detected by a wire reeling supervisor terminal.

An American Robot Merlin 600 performs the wire termination tasks (See Figure 3). The robot picks up the canisters from the wire reeling table and takes them to a termination rack where various equipment is located for wire stripping, twisting, lugging, crimping and soldering. Once the robot has terminated each end of the wire, the canister is placed in a wire queuing rack. All errors encountered during termination are monitored by a wire termination supervisor terminal.

The wire queuing rack acts as the material handler between the Termination Robot and the Wire Layup Robot (See Figure 4). There are two canister stations located on the rack. The station will rotate 180 degrees so that the wires will be made available for the layup robot. After wire layup, the empty canisters are inserted back into the wire queuing station for pickup by the termination robot who returns the empty canister to the reeling table. This system is monitored by a Wire Queuing Supervisor terminal for errors during operation.

The wire layup process is performed by an IBM 7565 gantry style robot (See Figure 5). The robot is controlled by an IBM Series I computer and runs on AML software. The robot inserts wires into connectors and lays up the wire harness. There are various fixtures which are used on the formboard of the layup robot. Gates are used to hold wires in place so that tie wraps may be placed by the robot. Breakouts are used to hold wires which will be processed later.

Hardware/Software Interfaces:

AUTOCAD version 2.6 is the minimum release required in order to use the AUTOLISP programming capabilities. The minimum system requirements for the use of AUTOCAD 640k RAM, 10 megabyte hard disk, and an RS-232 Serial Port. A math coprocessor may be used to increase the speed of the program.

There are two communication software packages that are used to transfer the AUTOCAD wire harness data form the PC to the VAX. PROCOMM is a communication software package which allows the user to perform automatic logons to the VAX through a PC. Once the user is logged on to the VAX, KERMIT communication software is executed. KERMIT software can be set up for the transfer of files from a microstation to a VAX. Autocad data files are transferred from the PC to the VAX using KERMIT. The hardware used for this transfer is a standard RS-232 serial connection. After the harness data files from Autocad have reached the VAX, the manipulation of the text format is accomplished by a Design Data Post Processor. All data is converted from the AUTOCAD format to RWHAS input file format.

Design Data Post Processor:

After ATTEXT is executed, AUTOCAD is exited and the program TRANS.COM is run. The input to TRANS is the ATTEXT output file

TXT. The TRANS program is written in Pascal and executes on a standard PC. Trans looks at each record in the input file and determines whether that line contains data from a connector, gate or tie by looking at certain fields in the record. After determining the record type, the information that is needed by RWHAS from that record is written to the intermediate data file INTERM.DAT in the format required by RWHAS. This step writes the proper information to each record, but does not order the records in the required sequence. This is continued until a "blank" record in the RWHAS.TXT file is found. This signals the end of the connector/gate/tie data section. INTERM.DAT is closed as an output file and reopened as an input file. This information is sorted according to record type. Connector data is written to the output file DATAPUT.DAT, then gate data is written. The input records from RWHAS.TXT now contain "Route" information. This data is read, reformatted and written to the file OUTPUT.DAT. The end of "Route" information is indicated by another blank record. "Tie" data is then read from the file INTERM.DAT. The end of "Route" information is indicated by another blank record. "Tie" data is then read from the file INTERM.DAT and written to OUTPUT.DAT in the proper format. OUTPUT.DAT now contains the harness design information in the proper format needed by RWHAS for fabrication. OUTPUT.DAT is then used as the input file for the RWHAS data generator program. See Figure 5 for flow chart of system.

Conclusions:

As a result of our research, wire harness design was integrated with wire harness fabrication. This resulted in a fully automated

CAD/CAM system. The technology resulting from this research may also be applied to other automated processes through the extraction of pertinent data from CAD drawings.

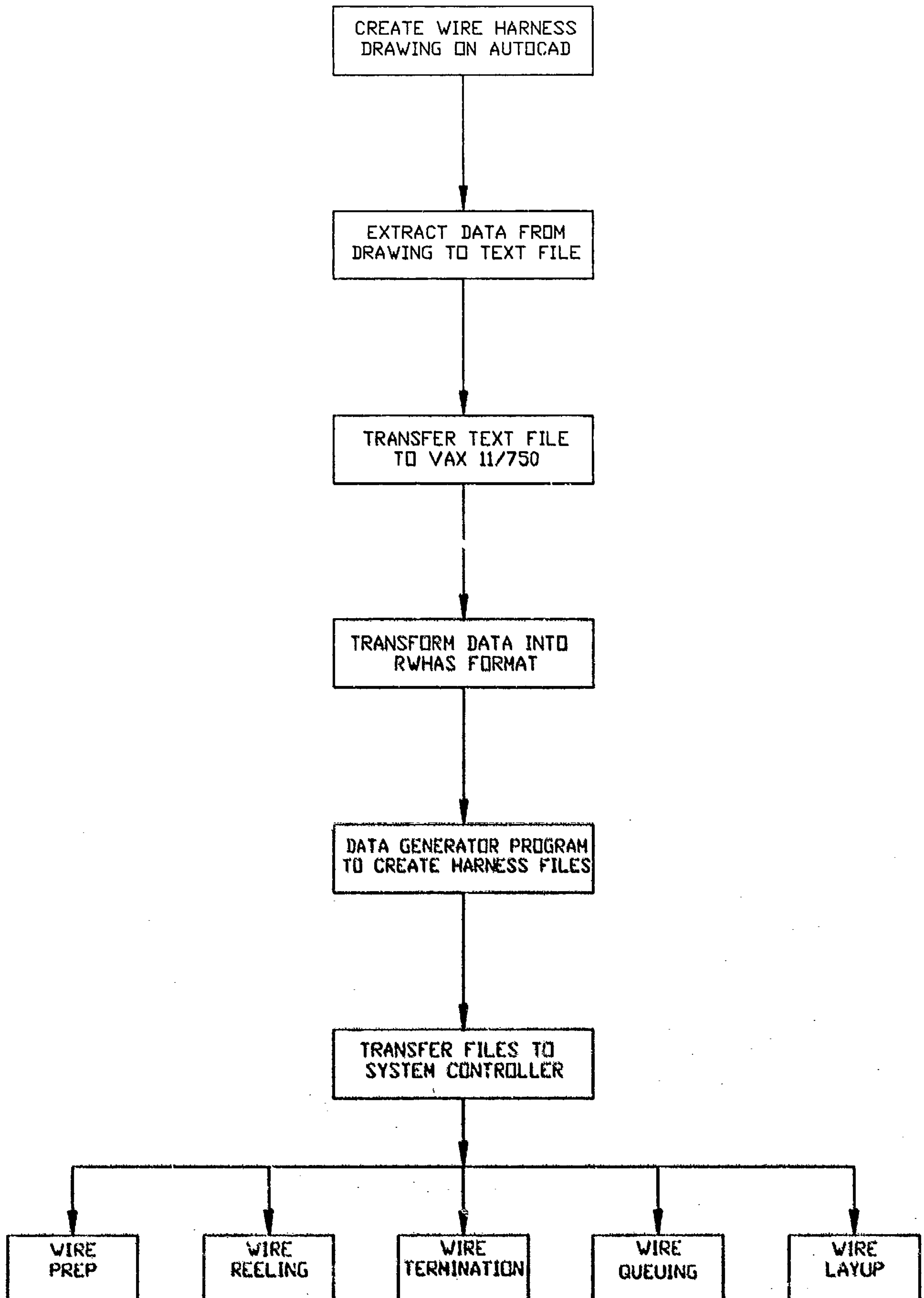

CREATE WIRE HARNESS DRAWING ON AUTOCAD
EXTRACT DATA FROM DRAWING TO TEXT FILE
TRANSFER TEXT FILE TO VAX 11/750
TRANSFORM DATA INTO RWHAS FORMAT
DATA GENERATOR PROGRAM TO CREATE HARNESS FILES
TRANSFER FILES TO SYSTEM CONTROLLER
WIRE PREP
WIRE REELING
WIRE TERMINATION
WIRE QUEUING
WIRE LAYUP

Figure 1

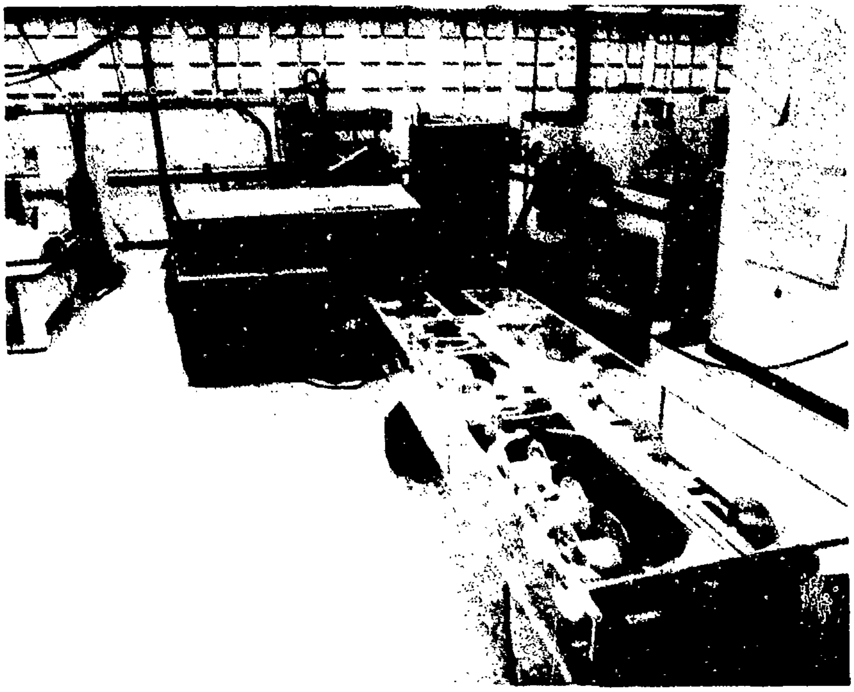


Figure 2 Wire Preparation Cell

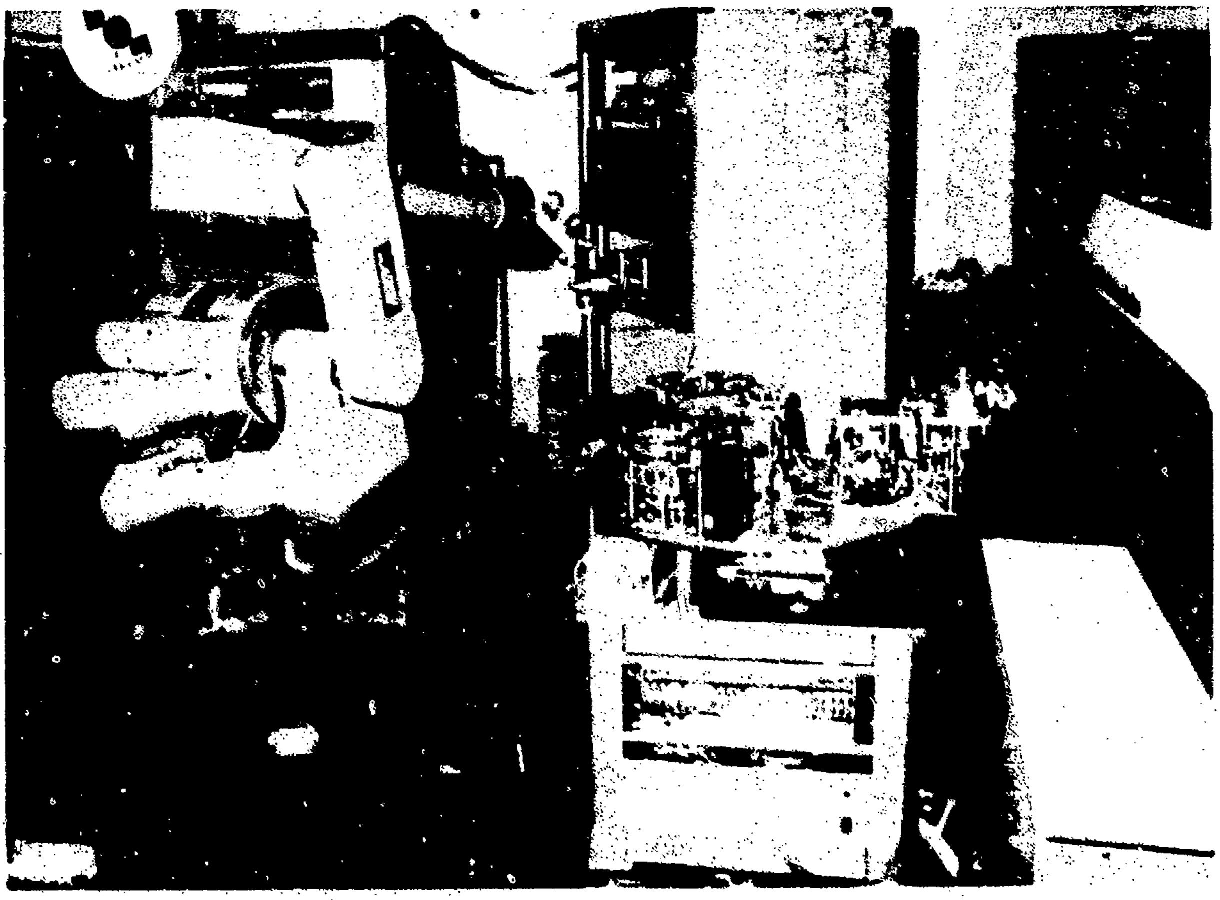
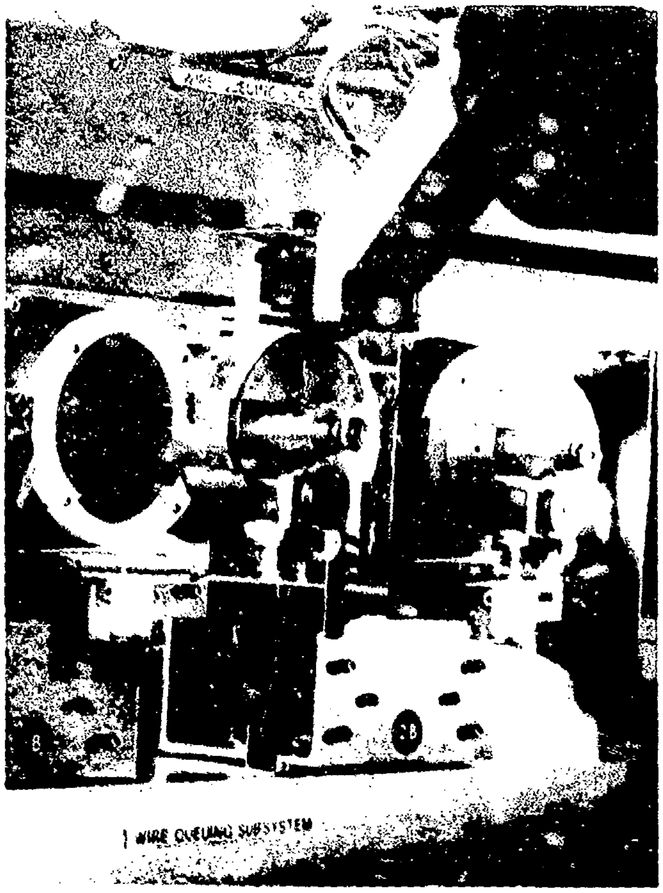


Figure 3 Wire Reeling and Termination Cell

Figure 4
Wire Queuing Cell



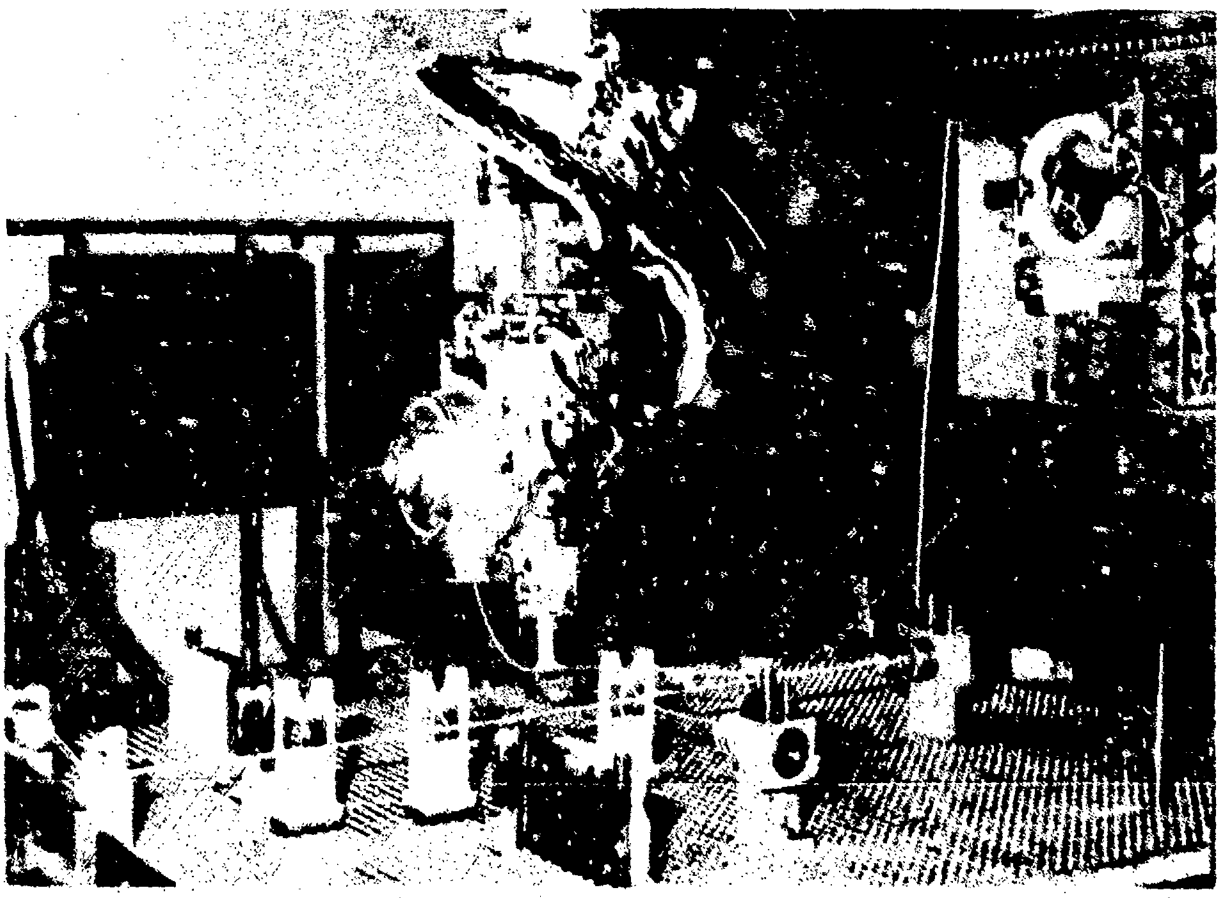


Figure 5 Wire Layup Cell

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Session VI Program A

Telerobotics

Chair: Cindy Coker, NSAS/MSFC

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Presented at the Conference on Space and Military Applications of Automation and Robotics

21-22 June 1988 **GACIAC PR 88-02**

TESTING THE FEASIBILITY OF USING A TELEOPERATED ROBOT FOR REMOTE, DEXTEROUS OPERATIONS

30 May 1988

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ABSTRACT

This project assessed the feasibility of using a teleoperated robot to perform certain procedures associated with nuclear test facilities and space station operations. Only the space station procedure is reported here. The teleoperated robot being evaluated was the SAMSIN Servomanipulator. The ratio of slave/master reflected-force feedback was varied so that either x:o (none), 4:1 (weak), 2:1 (moderate) or 1:1 (realistic) amounts of reflected force were experienced by the operator. Visual feedback was by means of 3 closed-circuit television monitors.

Twenty-eight (28) novice operators were trained to execute with the SAMSIN teleoperated robot the following simulated space station task: disassemble and reassemble a space station truss node. The total of 28 novice trainees was randomly divided into four groups of 7 operators each. Each group learned to execute the task with SAMSIN using one of the 4 reflected-force feadback rations. Training for each individual participant consisted of 3 sessions of about 2.5 hours duration each (for all tasks). The following results were obtained:

1. All operators performed all tasks at least once in the 7.5 hours.
2. Large individual performance differences were observed among the trainees.
3. The 2:1 force ratio group showed a slight advantage on early trials.
4. After 4 trials, performance was not different among the 4 groups.
5. After training, the task required an average of 7.3 minutes to complete.
6. After 4 trials, both errors and completion times were reduced by half.
7. After training, non-recoverable errors were practically non-existent.

The results proved the feasibility of using a teleoperated robot with a person in the loop to perform a simulated space station-related task. Total system performance - machines, people, training and procedures - was demonstrated for this truss node operation.

1.0 INTRODUCTION

The present report describes the results of an investigation into the feasibility of using a teleoperated robot to perform certain tasks in nuclear test operations as well as space station maintenance. Only the space station related task is reported here. The investigation was conducted for the Nuclear

Effects Division of the U.S. Army White Sands Missile Range. The experiment itself was conducted at the Robotics Laboratory of the NASA Goddard Space Flight Center.

The use of remote manipulators and teleoperated robots in a space environment has the potential to dramatically reduce human exposure to dangerous situations. Remote manipulators and teleoperated robots, often called master-slave devices, can be used instead of extra-vehicular activity (EVA) in order to execute operational and maintenace tasks that must be performed external to the space vehicle or space platform. With such devices, the human operator can be an astronaut working within the protected environment of a space vehicle, or even a person controlling a master console located on earth. In either case, the feasibility of training operators to remotely perform such space-related tasks becomes an important issue. The present experiment explores training completely novice operators how to remotely assemble and disassemble a space station truss mode using a SAMSIN teleoperated robot.

For certain operational and maintenance activities, reflected-force feedback could provide a valuable cue to the operator. Reflected-force feedback supplies the operator of a teleoperated device with a sense of touch. Many maintenance tasks require controlled amounts of force to execute, e.g. removing and installing a fitting with a wrench, or torquing down a nut. Without reflected-force feedback early operators have been known to break or destroy the objects that they were working on. Thus, in the development of teleoperated master-slave robots, the incorporation of reflected-force feedback became an early goal for engineers and designers of such remote devices. The present investigation explores the usefulness of such feedback in executing a space-related task.

2.0 METHOD

2.1 RESEARCH PARTICIPANTS

The research participants were 28 novice operators between the ages of 18 and 57 years. The group consisted of 17 females and 11 males. Each participant was paid $75.00 for approximately 7.5 hours of work, divided into three sessions of about 2.5 hours each. All participants had to be United States citizens in order to gain access to the NASA facilities.

2.2 APPARATUS

The research participants executed simulated tasks on a SAMSIN - 25 (Servo-Actuated Manipulator System with Intelligence Networks) Telerobot. SAMSIN is a master/slave manipulator with seven degrees of freedom. SAMSIN permits natural operator motions and has bilateral reflected-force feedback. The amount of force feedback reflected in the master arm can be varied to correspond to 0, 1, 1/2 or 1/4 times the force encountered by the slave arm. Reflected-force feedback was varied as a parameter of the present study. The 28 research participants were randomly partitioned into four (4) groups of seven (7) participants each. Each group received a different degree of reflected-force feedback in the master arm controller. The amount varied from no force feedback at all (0:x), to a realistic amount (1:1), with two intermediate amounts in between (1:2, moderate; and 1:4, weak). Each group experienced only one reflected-force feedback condition.

Each research participant sat in a chair in front of the SAMSIN master arm, which was suspended from above. Only one SAMSIN master/slave arm was used. Each participant viewed the operations and movements of the slave arm through three (3) closed-circuit television monitors. Three (3) black and white cameras were mounted near the slave arm (right, left and top views) and were remotely controlled by the experimenter. Each participant received identical viewing angles for the various tasks and subtasks performed.

2.3 PROCEDURE

Before the main experiment began, all participants were screened over the telephone for any physical or perceptual disabilities that might not allow them to manipulate the telerobot. Those who qualified for the experiment were scheduled for three appointments of approximately 2 1/2 hours each. Participant trainees were then randomly assigned to one of the four force-ratio groups (0, 1, 1/2, 1/4).

The trainee was given a detailed explanation/demonstration of how to use the master-hand controller to guide the slave arm, including time to practice stacking some wooden blocks. The trainee was then brought to the workstand to see the task setup, to have the task and subtasks explained to him/her, and to perform the task by hand before performing it on the telerobot. This task-acquaintance procedure was conducted before learning each of the five (5) tasks. Only the last task, the disassembling and reassembling of a simulated space station truss node, is reported on here.

3.0 RESULTS

3.1 LEARNING THE TASKS WITH SAMSIN

All 28 research participants completed all 5 tasks at least once in the 7.5 hours of testing. Thus all 28 novice participants learned to execute the space truss node assembly task. The number of trials completed depended greatly on individual differences among the trainees. The number of trials ranged from 1-4. Some participants learned quickly, performed the tasks rapidly and made a minimum of errors. Others had considerable difficulty learning the tasks, took longer and made more errors. In the final analysis, 78 percent of the participants completed all 4 trials for every task, i.e., they completed the entire experiment.

When the space station truss node data were collapsed across all participants in each group, some interesting results were found. Figure 1 shows the average time to complete the truss node task for each group of trainees as a function of the trial number. Figure 2 shows the average number of errors made on the truss node task for each group of trainees, also as a function of trials. In both Figures 1 and 2 the parameter distinguishing the four (4) curves is the reflected-force feedback ratio.

By far the most prominent effect observed in the present experiment was the strong influence of practice on the truss node task performance. Linear regression equations fit to 8 curves depicted in Figures 1 and 2 all had negative slopes. These uniformly negative slopes revealed that, irrespective of reflected-force ratio, and irrespective of whether the metric was time or errors, performance improved with repeated practice. Analysis of variance on the data from the entire experiement (all tasks) confirmed this strong training influence. In general, both the average time to complete the truss node task and the average number of errors made were reduced by about `-lf over the course of the four (4) trials. After training, the average time to complete the task was about 7.3 minutes, and the average number of minor errors made was about 6. Non-recoverable errors (e.g, droping a part of the truss node) became practically no existent.

3.2 EFFECT OF REFLECTED-FORCE FEEDBACK

One of the major goals of the present experiment was to assess the effect of reflected-force feedback on the ability of the research participants to execute the various tasks. In this regard certain trends seem evident from inspection of Figures 1 and 2. It would appear that, in the early stages of learning, the group of participants with the 1:2 reflected-force ratio generally performed the tasks faster and made fewer errors compared with all other groups. However, after trainees in the other groups performed the tasks 3 or 4 times, there was little difference in either average performance time or average number of errors among the four groups of participants.

The apparent initial advantage of the 1:2 reflected-force ratio was only confirmed by statistical tests for the data concerning times to completion (Figure 1) and not for the data concerning errors (Figure 2). The error data generally showed more variability than the time to completion data, making observed differences more difficult to demonstrate statistically. Thus, in conclusion, the present experiement revealed a slight initial advantage in the time to complete novel tasks when using the 1:2 reflected-force ratio. This difference disappeared with training, however.

4.0 DISCUSSION

The results of the experiment proved the feasibility of using a teleoperated robot with a person in the loop to perform a simulated space-related task. Total system performance -- machines, people, training, and procedures -- was demonstrated. Novice operators learned to perform all the tasks with only about 7.5 hours of training. Initially, an optimal ratio of reflected-force feedback proved somewhat beneficial in performing the task on the first few trials. With repeated practice, however, operator training was able to compensate for the lack of reflected-force feedback. Thus, when novel tasks are employed, reflected-force feedback may assist as an added stimulus input cue to the operator so as to facilitate task performance during the learning stage. For familiar or well-trained tasks, reflected-force feedback may not be as important a factor in executing certain teleoperated procedures, especially in situations where good visual cues are provided.

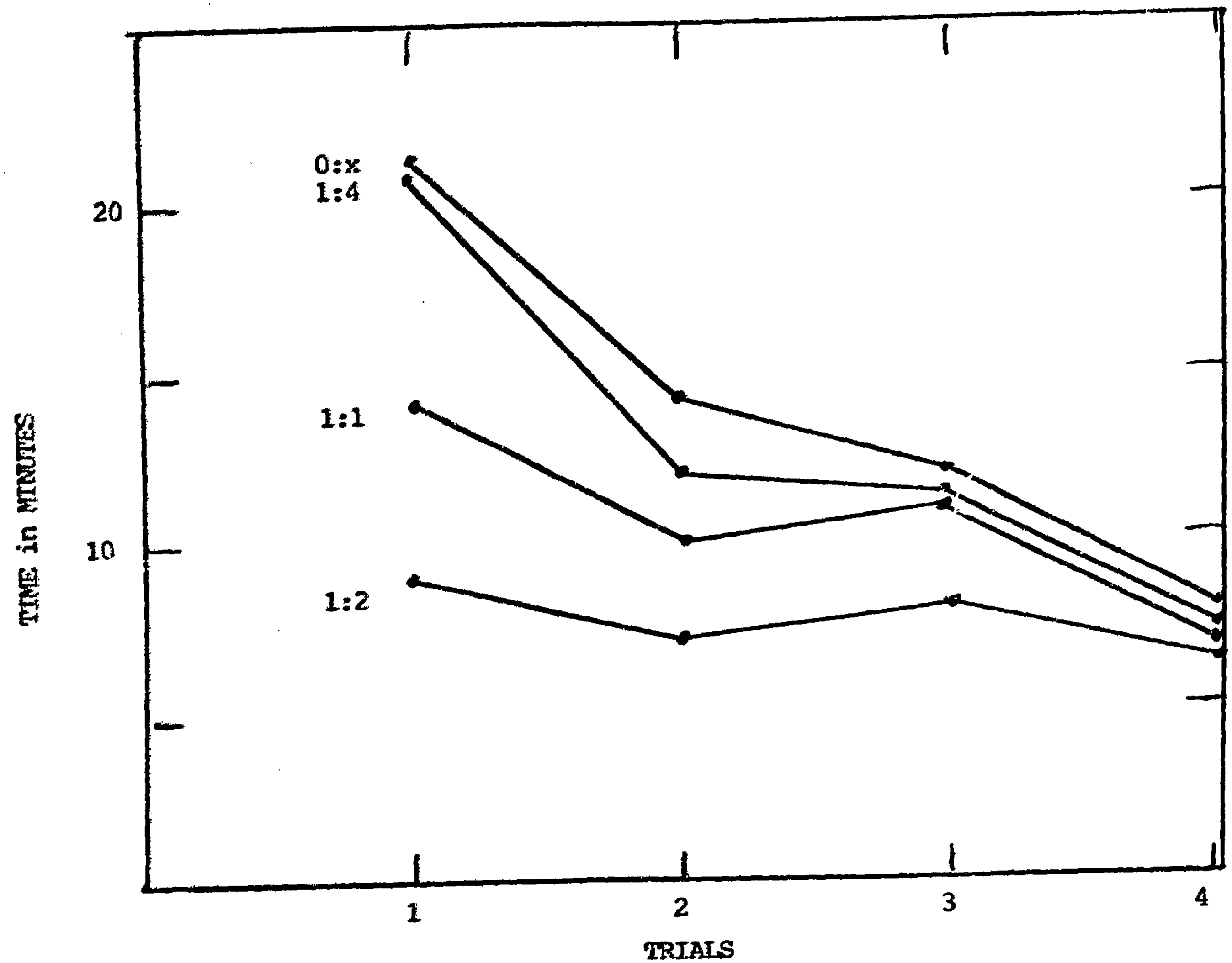

Figure 1. Average time to complete the truss node task as a function of trials. Reflected force ratio is the parameter.

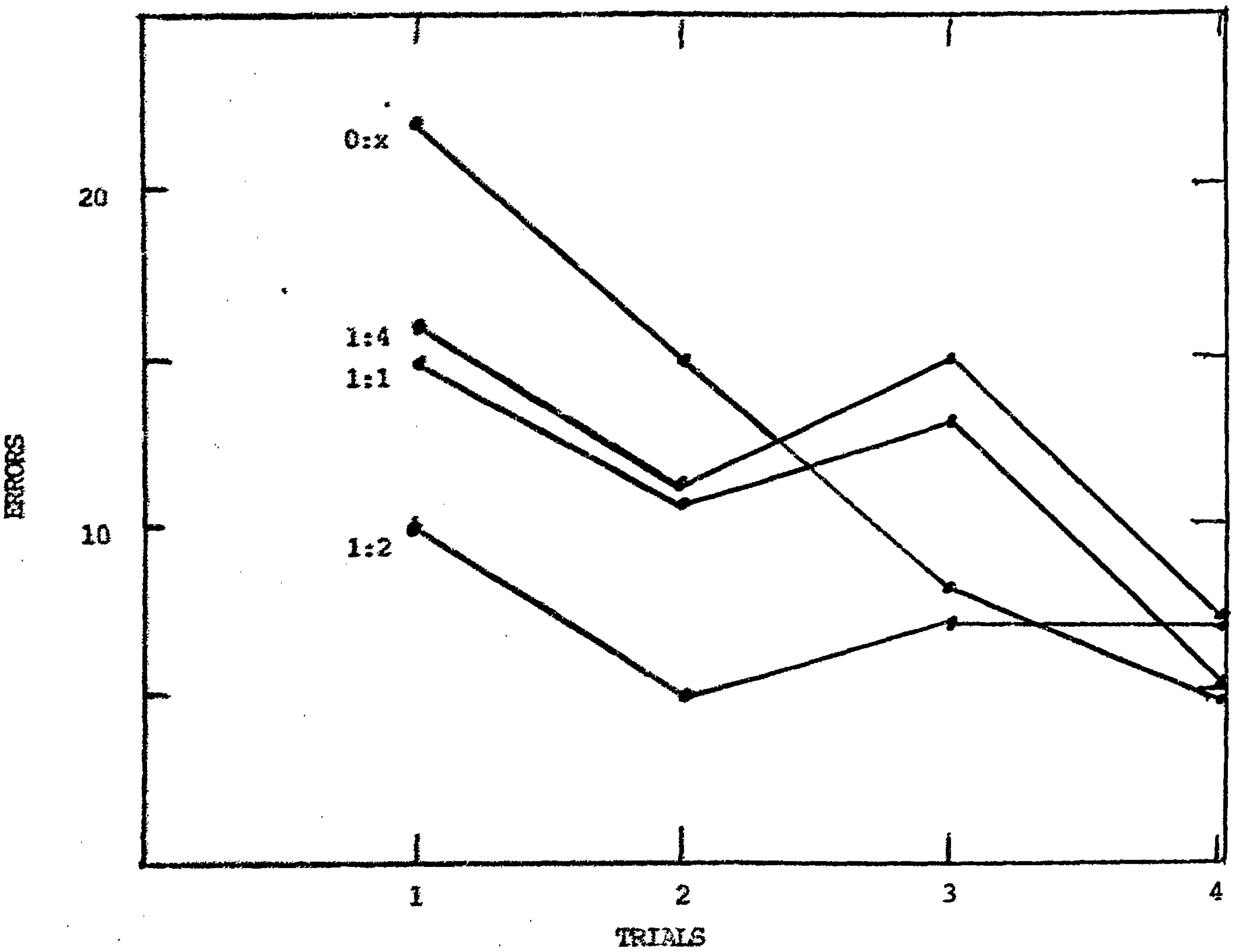

Figure 2. Average number of errors made executing the truss node task as a function

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21-22 June 1988 GACIAC PR 88-02

ORU GUIDELINES FOR TELEROBOTIC COMPATIBILITY

21 June 1988

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ABSTRACT

This paper describes how Rockwell International's Space Transportation Systems Division developed interface guidelines for orbital replacement units (ORU's) by characterizing on-orbit telerobotic devices that would service the units, by identifying interface guidelines for compatibility between the servicing device and the ORU's, and by verifying the guidelines in a robotics laboratory. Benefits of standardized ORU interface designs are also discussed.

1.0 INTRODUCTION

The amount, cost, and complexity of on-orbit equipment will increase significantly over the next decade. Much of this equipment will require recurring on-orbit maintenance, typically by changeout of orbital replacement units (ORU's). (ORU's are defined as the level at which failed or soon-to-fail components are replaced in orbit.)

Rockwell International's Space Transportation Systems Division (STSD) in Downey, California, is aware of the pressing need to design equipment that can be readily maintained in orbit. Therefore, the division is developing guidelines for ORU connectors, containers, racks, and packaging that easily accommodate on-orbit maintenance. And because crew extravehicular activity (EVA) is not always possible for on-orbit maintenance tasks, STSD has stressed interface guidelines that are compatible with changeout by a telerobotic device as well as by an EVA crew person.

STSD's approach emphasizes standardization of ORU interfaces, which become identical for as many ORU's as possible. For example, one may wish to limit the variety of load-bearing fasteners to two types (large and small for high and low loads) and use only one standard electronic packaging type, making all packages multiples of that one type (like the ARINC system in the commercial airline industry). This approach offers useful guidelines for designers as well as cost savings and other benefits (discussed in the last section of this paper).

This paper, which describes the development of ORU interface guidelines to date at STSD, is divided into four sections: **Telerobotic Capabilities** discusses the assumptions we made about the characteristics of on-orbit telerobotic devices that perform ORU changeout and create compatibility requirements for any ORU interface. **Interface Development Method** describes the STSD procedures to identify and develop interface guidelines. **Laboratory Verification** describes preliminary guideline verification in the STSD Automation and Robotics Laboratory. **Benefits** summarizes the advantages of our approach.

2.0 TELEROBOTIC CAPABILITIES

ORU interface guidelines must be compatible with the capabilities of the particular agent (for example, flight telerobotic servicer, other telerobotic devices, or EVA crew person) that performs the changeout. For example, the motions required to undo a connector must be within the degrees of freedom and range of the agent performing the changeout.

The work at STSD considers the primary changeout agent to be a teleoperated force-reflecting manipulator with an EVA crew person as backup. Therefore, our first step was to define, at a high level, what such a teleoperated manipulator would reasonably be expected to reach, grasp, manipulate, and so on. The EVA teleoperator assist robot (ETAR), a Rockwell concept that has been described extensively elsewhere,† is based on requirements to change out a general set of ORU's, including types that are very common or fragile, or require very dexterous manipulation. ETAR capabilities are summarized below only insofar as they relate to ORU interface.

Arm configuration—The ETAR arm is "human-like" with a shoulder, elbow, and wrist. Therefore, ORU's cannot be designed that require multiple-joint "snake-like" motions for changeout.

Degrees of freedom—ETAR has seven degrees of freedom: shoulder pitch and yaw, elbow pitch and yaw, and wrist pitch, roll, and yaw. ORU's designed with bolts or other fasteners requiring 360-degree revolution without a special tool are, therefore, compatible with this type of wrist.

Size—We found that an arm link length of shoulder to wrist with arm/shoulder separation of 0.75 meter accommodates the set of ORU's that formed the basis of the ETAR size requirements. This arm size could then be the basis for sizing ORU's that are within the arm's reach and transport capabilities.

Operational characteristics—With the human arm as a reference point, we identified a steady force of 90 N with a peak capability of 135 N and a maximum speed of 1 m/sec as reasonable for ETAR operations. These parameters provide guidelines for the kinds of forces ORU changeout requires without special tools.

3.0 INTERFACE DEVELOPMENT METHOD

ORU guidelines were generated in four phases:

- ORU identification
- ORU interface requirements
- ORU interface concept guidelines
- Laboratory verification

As part of this process (Figure 1), we interfaced and consulted with engineers responsible for different subsystems, two knowledgeable astronauts, team members, and several potential vendors. We also visited Continental Airlines maintenance hangars and discussed commercial airline maintenance procedures and their application to on-orbit maintenance.

†Clarke, M.M., W.M. Thompson, and C.J. Divona. *Requirements and Conceptual Design of the Manipulator System for the Extravehicular Teleoperator Assist Robot (ETAR)*. Rockwell International, Space Station Systems Division, SSS 86-0139 (Nov. 1986).

Clarke, M.M., C.J. Divona, and W.M. Thompson. "Manipulator Arm Design for the Extravehicular Teleoperator Assist Robot (ETAR): Applications on the Space Station," *Proceedings—First Annual Workshop on Space Operations Automation and Robotics* (SOAR '87). Lyndon B. Johnson Space Center (Aug. 1987), pp. 471-475.

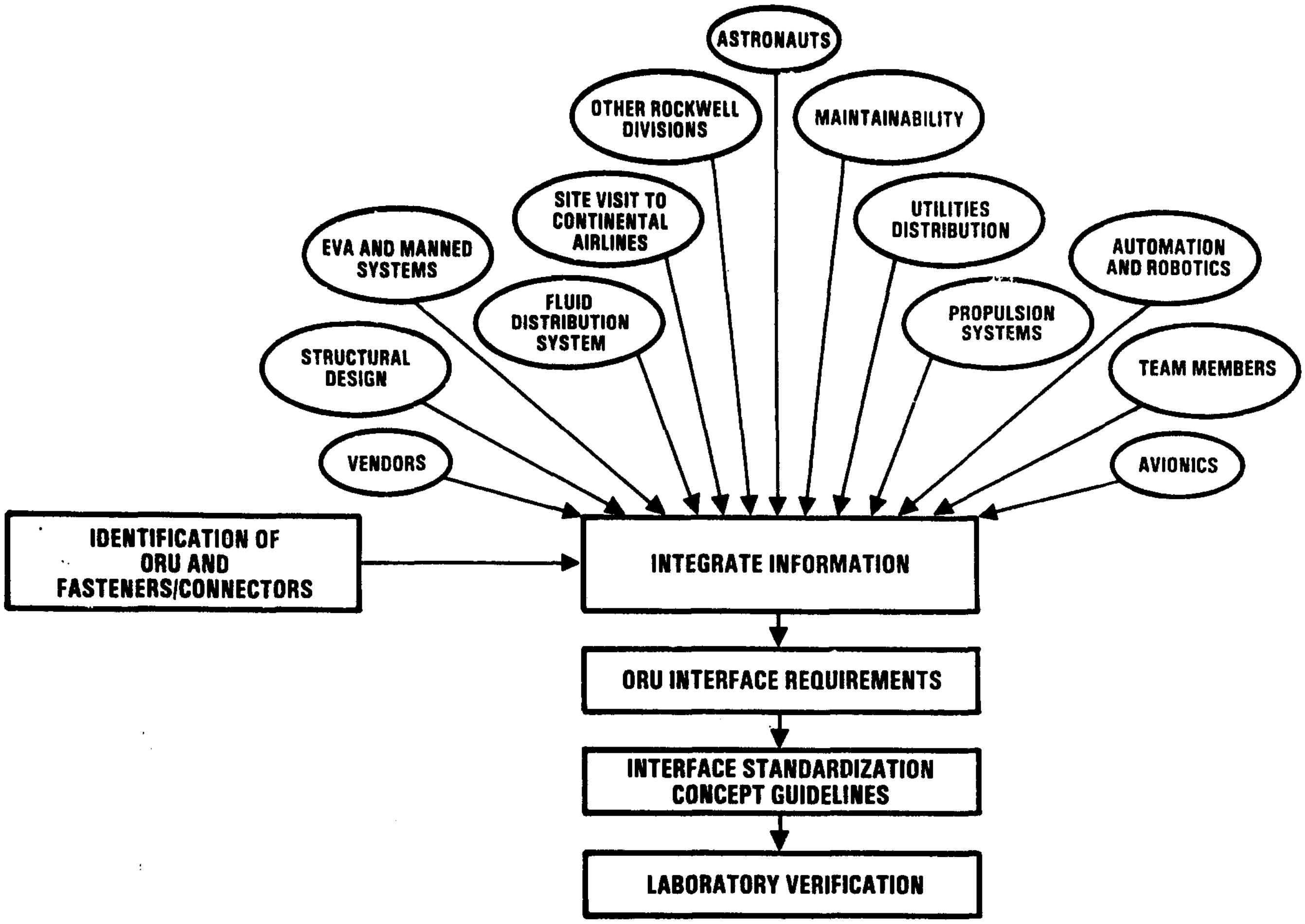

Figure 1. ORU INTERFACE DESIGN PROCESS UTILIZED A BROAD SPECTRUM OF DATA BASES

3.1 ORU IDENTIFICATION

Our data sources included NASA documents, relevant architectural control documents, requirements documents, and white papers as well as our own contract and R&D activities. We identified eight typical types of ORU's:

- Communication and tracking
- Guidance, navigation, and control
- Data management systems
- Fluid distribution
- Propulsion
- Heat rejection and transport
- Mechanical/structural
- EVA-associated equipment

Data were also collected on estimated mean time between failures and mean time to repair for these ORU's. In this way, we gave special attention to "maintenance significant" ORU's (those that require frequent or time-consuming maintenance operations).

3.2 ORU INTERFACE REQUIREMENTS

We next undertook a detailed study of interface requirements for these ORU's. Our most important data collection tool was the Rockwell ORU Interface Requirements Questionnaire, which was the basis for numerous interviews with system designers. The questionnaire covers ORU interface requirements in 12 areas—for example, mass, size, location, maintenance operational forces, identification, etc. Useful data were also gathered from other sources, such as interviews with former astronauts and team members, site visits to commercial airline maintenance facilities, and a detailed review of applicable documents.

The information was then reorganized to produce requirements for four types of interfaces:

- Mechanical fasteners
- Electrical/fiber-optic connectors
- Fluid connectors
- Racking and packaging of ORU's

These four major sets of ORU interface requirements were then further defined. For example, mechanical fastener requirements were further categorized:

- Rack mounting
  - With cold plate
  - Without cold plate
- High load bearing
- Operationally induced loads
- Temporary fasteners for launch loads

In addition, fastener requirements stressed ease of operations, whether the operation was one performed by telerobot or by an EVA crew person. It was important for motions to be the same for as many fasteners as possible—motions that are simple, requiring less than a 180-degree turn and minimum use of tooling. ORU's requiring fluid connectors were also placed in a set, and this set was further broken down according to type of fluid, pressure, line size, and so on. Similar procedures were followed for electrical/fiber-optic connectors and racks and packages.

3.3 INTERFACE STANDARDIZATION CONCEPT GUIDELINES

From the requirements described above, we were able to identify candidate standardization concept guidelines for mechanical, electrical, fiber-optic, and fluid connectors and racks. For example, our concept of the fastener for a standard data processor (SDP) electronic black box (Figure 2) utilizes an EVA hand-hold bar that can be pulled forward to trigger a clamping action that presses on a flange to secure the SDP (black box) in the rack (Figure 3).

It is important to note that these candidate standardization guidelines referred to sets of ORU's rather than particular ORU's. Therefore, we would expect not only the SPD but also a wide variety of other types of electronic ORU's to be packaged in this type of box with this type of connector.

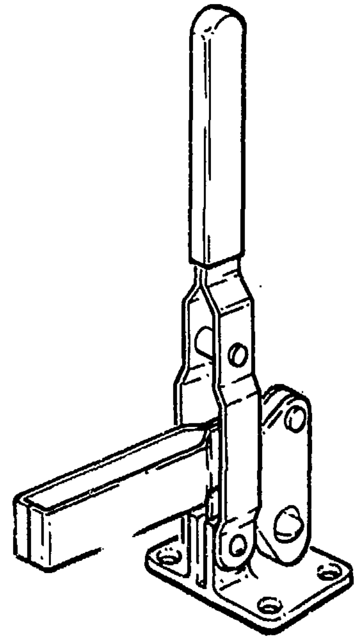

Figure 2. SIMILAR TYPE OF FASTENER WAS USED IN SDP DESIGN

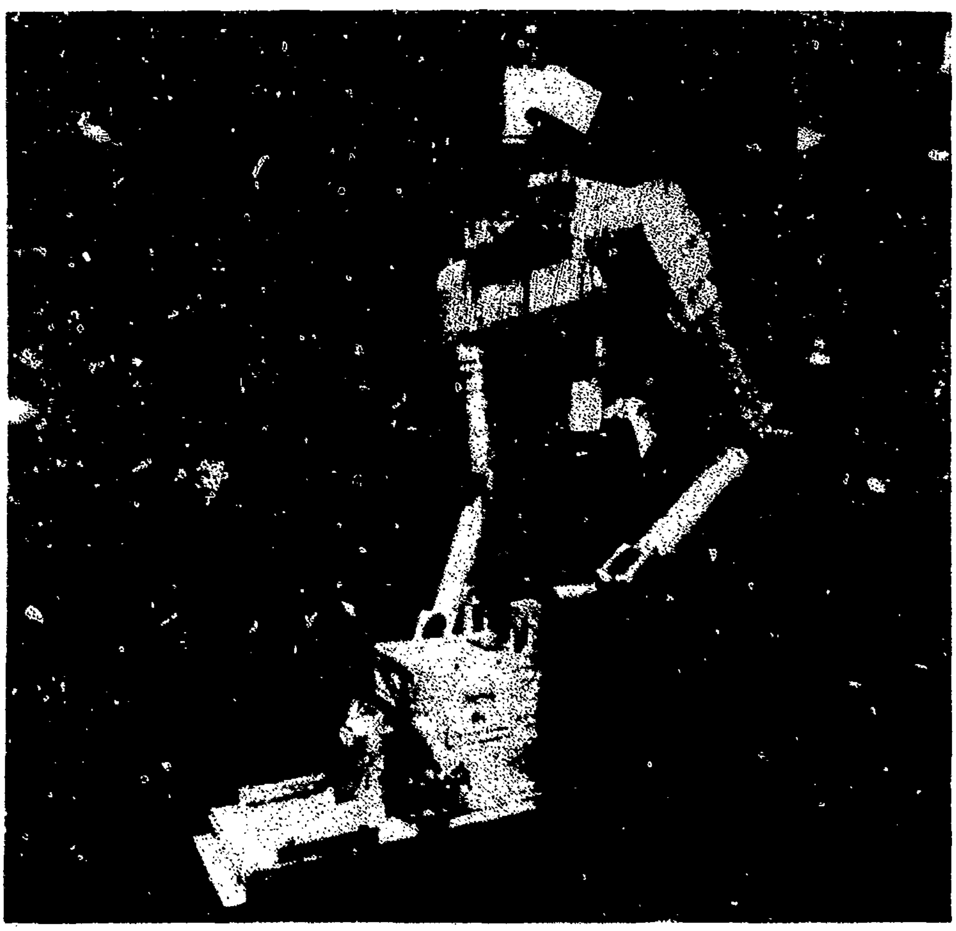

Figure 3. SDP REPLACEMENT WAS VERIFIED BY A TELEOPERATED SYSTEM

The last phase of our program involved mockup and verification of these fastener/connector concepts in the Rockwell Automation and Robotics Facility (Figure 4). The facility contains an electromechanical teleoperated manipulator with two seven-degree-of-freedom slave arms driven by a replica master. The facility also contains a four-degree-of-freedom transporter to move the slave through its work place. Cameras are aboard the slave and fixed at other locations in the work place.

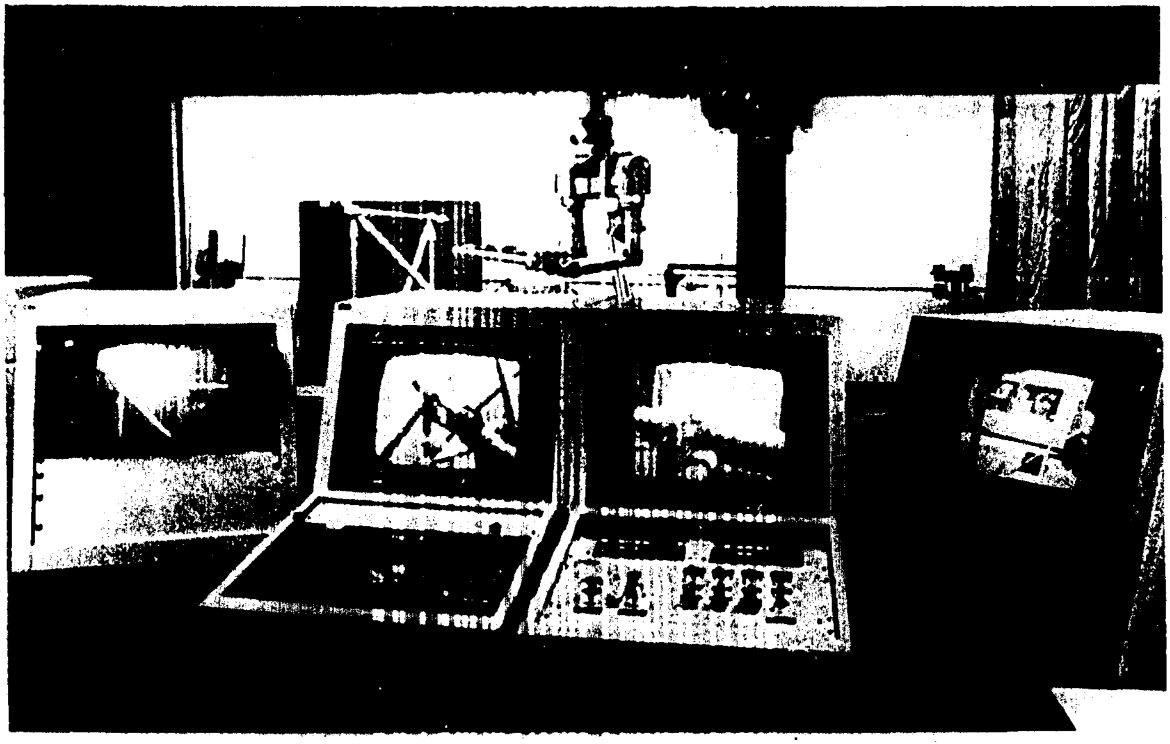

Figure 4. FASTENER/CONNECTOR CONCEPTS WERE VERIFIED IN ROCKWELL'S AUTOMATION AND ROBOTICS FACILITY

Task boards contain mockups of a large variety of ORU's. Among others, a passive full-scale mockup was built of the SDP ORU described above (Figure 3) to be compatible with both EVA and robotic ORU design guidelines.

The SDP slides in position (along a rack) guided by a built-in key design. The electrical and fiber-optic connectors are all blind-mated and self-aligned. These connectors are located in the back of the unit. The SDP can be secured in position by a simple forward motion of a handlebar designed like an EVA hand hold. This handlebar is part of the rack and generates enough force to ensure proper contact with the cold plate located under the SDP. Telerobotic compatibility with this mechanical interface was demonstrated when the facility's teleoperated manipulator changed out the SDP (Figure 3).

5.0 BENEFITS

The standardization of connectors among many ORU's results in numerous benefits. Costs for DDT&E of connectors and racks as well as crew training are reduced because the number of different types is reduced. Fewer spares must be warehoused. Fewer varieties of tools and end effectors are required. The capability to reconfigure is increased. Future automation becomes more efficient because of standardized end effectors, less robotic software must be written than what would be required if interfaces varied greatly among ORU's, and the entire Space Station integration effort would benefit from common fasteners across all four work packages.

Ground Control of Space Based Robotic Systems

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The ability to control robotics in space is clearly an established art with the success of numerious unmanned space probes by both the U.S. and the U.S.S.R. However, these vehicles, such as the Lunakhod and Voyager, were designed to perform discrete functions, and months and years of analysis and programming were required to confidently accomplish even simple planned functions. With the advent of Space Station operations, there will be many instances where robotics will be needed to respond quickly to variable sets of environmental parameters.

A system for ground control of space robotic systems is presented and the various control paradigms and operational modes are discussed. The safety aspects, operational constraints and design considerations for robotics operation in a manned environment are discussed.

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THE ADVANCED RESEARCH MANIPULATOR I

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ABSTRACT

The Advanced Research Manipulator I (ARMI) is a lightweight 6 degree of freedom manipulator designed to support laboratory and military field telerobotics research. This paper describes the design of the manipulator and proposed research. The ARMI weighs 140 lb_f and has a continuous payload of 70 lb_f at a full extension of 7 ft. This payload to weight ratio of 1 to 2 is achieved, with a conservative design, through the use of advanced composite links, lightweight harmonic drive gear reducers, high density motors, and ultra-lightweight ball bearings. The ARMI, in addition to its extremely light weight, has several other unique features. One of the most significant is the extensive use of space qualifiable technologies and components. The motors, harmonic drives, bearings, composite materials, and lubricants have all been used in previous space applications. Further, the controller and gripper are potential candidates for future space telerobotics applications. The ARMI controller is the JPL-developed Universal Motor Controller (formerly the Universal Computer Control System) and the gripper is an NBS/NASA parallel jaw gripper modified for electric actuation. Other major features include modular joint designs and the ability to alter easily link lengths and stiffnesses by varying the composite lengths, materials, and/or winding patterns. This design flexibility provides significant opportunities for research in the areas of flexible manipulators, long reach manipulators, and the properties of advanced composites as link materials. The light weight of the ARMI and rugged design make it an ideal tool for researching the possible uses of manipulators aboard teleoperated vehicles. Current plans include mounting the ARMI on a lightweight teleoperated vehicle to investigate the utility of manipulators for placement of various sensors, clearing obstacles, and enhancing vehicle mobility.

1.0 INTRODUCTION

The design of the ARMI (Figure 1) was initially driven by the need to provide a small teleoperated vehicle, the MINIBOT (Figure 2), with a manipulator to perform tasks such as emplacing mines and sensors and manipulating cameras.

Since the MINIBOT is a small vehicle with a limited payload of approximately 500 lb_f the design of the ARMI was driven toward a very lightweight manipulator. A limit of 200 lb_f was placed on the ARMI with a minimum payload of 50 lb_f. Through AAI's iterative manipulator design approach, the total weight of the manipulator was reduced to the present level of 140 lb_f and the payload increased to 70 lb_f. The manipulator possesses 6 degrees of freedom (dof) and has a reach of 7 ft.

In addition to supporting research aboard the MINIBOT the ARMI was designed to support space and laboratory manipulator research. These requirements were placed on the design since most of the lightweight components used in the ARMI design have been used both in previous space applications and in the design of prior laboratory manipulators.

In addition to the high payload to weight ratio and the use of space qualifiable technologies, design goals and drivers for the ARMI included: design modularity, design scalability, high stiffness, ruggedness, small volume, low cost, controller flexibility, and a general goal of pushing the state-of-the-art of lightweight/high payload manipulators to new levels.

The remainder of this paper discusses the mechanical design, controller and feedback elements, and research opportunities provided by the ARMI.

2.0 MECHANICAL DESIGN OF THE ARMI

The kinematic configuration of the ARMI is shown in Figure 3 and the Denavit - Hartenberg parameters [1,2,3] and joint rotational limits of the ARMI are listed in Table 1. Since the nature of the tasks to be performed by the manipulator is general, a 6 dof revolute configuration was selected. This configuration has a proven history for general purpose applications. The offset of link 1 permits the manipulator to reach over the edge of the MINIBOT vehicle.

Following the definition of the ARMI requirements, alternative mechanical drives were analyzed which could meet these requirements [4,5]. Cup-type harmonic drives were selected for the detail design since they resulted in the lightest and simplest joint designs. Additionally, harmonic drives were selected because of their high torque ratings, noncatastrophic failure mode, wide range of gear ratios, and previous use in space applications. Harmonic drives are also zero backlash reducers and can be modified at a low cost to increase stiffness and reduce inertia. Based on cup-type harmonic drives, two modular joint designs were developed, one for yaw joints and another for roll joints.

Lightweight, four-contact ball bearings, which are used on the Shuttle Remote Manipulator System, were selected because of their ability to withstand substantial thrust, moment, and radial loading. The use of these bearings simplified the design and assembly of the ARMI since they require no special preloading.

A dry lubricant, tungsten disulfide, is used as the lubricant for the harmonic drives and bearings since no provision for an oil bath for the harmonic drives could be made without increasing the complexity and weight of each joint. Tungsten disulfide is used in many space applications as a lubricant because of favorable outgassing characteristics and its extremely low coefficient of friction (0.03).

High-torque, lightweight, brush motors actuate each joint. The motors used on the ARMI have been used in Canadian commercial satellite applications and in all of the teleoperated manipulators the Oak Ridge National Laboratory has developed. Power-off brakes and dual channel optical encoders are integral to each motor. The motors are lubricated with a synthetic grease qualified for space use.

Graphite/epoxy (G/E) composites are used to form links 2 and 3 of the ARMI. These G/E links substantially reduced the weight of the manipulator over an all aluminum design. As an example, the weight of link 2 was projected to be 20 lb_f assuming a constant cross-section aluminum box beam. By comparison, using a G/E link the weight was 3 lb_f. This not only reduced the weight of link 2 but also the weight of joints 1 and 2, which must support the link. The links are rectangular box beams wound by AAI with a 45 degree helix angle and with unidirectional plys at 0 degrees along the top and bottom (relative to gravity) of each link. The links are secured with fasteners since, as an experimental manipulator, the links are removable. The mandrels for winding were manufactured such that link lengths can be varied. The ARMI can be extended to a length of 11.75 ft. with composite links wound on the existing mandrels.

The gripper for initial testing is a version of the NBS/NASA Parallel Jaw Gripper [6], modified by AAI for electric actuation (Figure 4). The gripper was selected because of its simplicity of design, high gripping force, ease of modification, and because it is being considered by NASA as a candidate for space use. The gripper is actuated by an Acme thread, linear actuator that can apply up to 75 lb_f gripping force and is self locking.

3.0 CONTROLLER AND FEEDBACK ELEMENTS OF THE ARMI

The controller for the ARMI is an AAI modified version of the Universal Motor Controller (UMC). The UMC (formerly the Universal Computer Control System) is a developmental system from the Jet Propulsion Laboratory (JPL) capable of controlling any robot using DC electric motors. The UMC was selected because it met the design requirements of multiple applicability and light weight and is a candidate for possible use within NASA for telerobotics research on Earth and in space. The following discussion regarding the UMC is derived from previous publications by JPL [7,8].

The major hardware elements of the UMC are a joint level processor card, joint controller cards, and pulse width modulated (PWM) power amplifiers. The AAI UMC incorporates two joint controller cards and seven power amplifiers (six joint and one gripper motor). However, the UMC can support as many as four joint controller cards and 16 power amplifiers. The AAI controller components as well as a wire-wrapped encoder line driver are shown in Figure 5.

The joint level processor card consists of a 32016 microprocessor, floating point coprocessor, interrupt control unit, 32K ROM, 128K RAM, MULTIBUS interface, BLX bus interface, parallel port, and two serial ports. The joint level processor can be used to control up to four joint controller cards and can interface via a MULTIBUS to other MULTIBUS cards. These additional MULTIBUS cards can be used to perform such operations as calculating feedforward commands, solving inverse kinematic equations, or processing sensor data.

Each joint controller card controls up to four joints and for each joint incorporates an encoder interface, a digital tachometer, and a PWM power amplifier control unit. Each joint controller card also includes an A/D subsystem, an EPROM subsystem, on-board clock, and a BLX bus interface. Further, joint controller cards contain three general purpose digital inputs, four general purpose analog inputs, and eight general purpose digital outputs (currently unused). Figure 6 shows an electronic block diagram of a joint controller card.

The A/D subsystem measures motor current, motor power supply voltage, potentiometer position, and an additional external voltage per joint. The BLX bus interface permits the joint controller processor to address the registers on the joint controller card via the 32016 BLX bus.

Each joint controller encoder interface is comprised of a digital filter to reduce the effect of noise on the encoder inputs, a 12 bit up-down counter, a quadrature decoding logic to control the counter, an eight bit bus interface, and an inhibit logic to prevent the count from changing between reading of the high and low nibbles. Digital tachometers contain a bus interface, a direction detector register, motion detector register, and pulse time counter. The PWM power amplifier control units generate pulses that control the upper two MOSFETs in each power amplifier and the enables to control the lower two MOSFETs. The output of the PWM control unit is an eight bit command with sign.

The PWM power amplifiers are MOSFET H bridges that include short circuit protection and current feedback resistors (Figure 7). Failsafe brakes are activated through a high current on-off switch.

The UMC software incorporates several functions, some of which are: joint servo control, import and export of data from shared memory, import and export of data from parallel and serial ports, interpolation between setpoints, compensation for slowly changing variables such as supply voltage, hardware integrity verification, and user friendly interface for initialization, setup, and debugging.

UMC software has been written by JPL to maximize utilization of the processing power of the 32016 microprocessor while remaining flexible. This is accomplished by burning a code generator onto the system ROM and then, when the application is required, the code generator writes the program optimally for that application. Part of the benefit of this technique is that the software can modify itself to particulars such as the polarity of the motor, encoder, and/or potentiometer connections. This makes connection of a new manipulator relatively simple. In fact, after the connections are made, the user can turn the system on and tell the UMC how many motors are used, what maximum motor voltages and currents are, what the joint motion ranges are, what sensors are supported and their polarities, and what feedback gains are.

Currently, the primary operator control device for the ARMI is a joystick developed by the German Space Agency, DFVLR [9,10,11] (Figure 8). The joystick, the DFVLR Steering Ball, incorporates a compliant force/torque sensor within the hand grip. The Steering Ball can be used to generate position, rate, or force commands from the force/torque vector measured by the sensor. This provides a variety of control techniques, which maximizes the opportunities for addressing man-machine interfacing questions. Further advantages of the Steering Ball are low cost, small size, ergonomic design, and design for space application in the German ROTEX robotics experiments. Initial plans are to control the ARMI in the rate control mode.

4.0 RESEARCH OPPORTUNITIES WITH THE ARMI

The ARMI offers an assortment of research opportunities in both the laboratory and in the field. By using different types of composite links, the length and stiffness of the links can be altered. This capability supports investigations of the dynamic characteristics of advanced composite material similar to those conducted by B. S. Thompson, et. al. at Michigan State University [12]. Experimental research investigating the design of composite links could further theoretical efforts like those by J.S. Lamancusa at The Pennsylvania State University [13]. Long reach robotics research as well as flexible manipulator research will be supported by the ability to lengthen and vary windings and materials. Flexible manipulator and controls research can also be advanced by the ability to interchange motors and harmonic drives to create different combinations of motors, gear ratios, inertias, and joint stiffnesses. Controls research can be further supported by modifying existing UMC software to permit different control algorithms to be tested. Additionally, because of the use of space qualified technologies, the ARMI can be used to appraise these technologies for space manipulator design.

Since the ARMI is designed to be mounted on a vehicle, research of military applications of manipulators is possible. The ARMI can be used to investigate the use of manipulators with small teleoperated vehicles in combat operations and field testing of military logistic concepts.

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6.0 ACKNOWLEDGEMENTS

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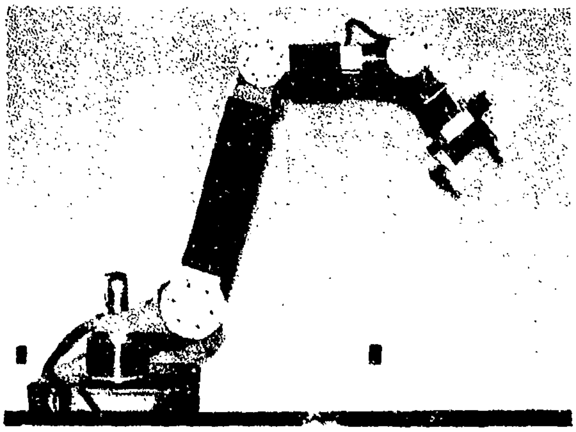

Figure 1. The AAI Advanced Research Manipulator I.

Figure 2. The AAI MINIBOT Teleoperated Vehicle.

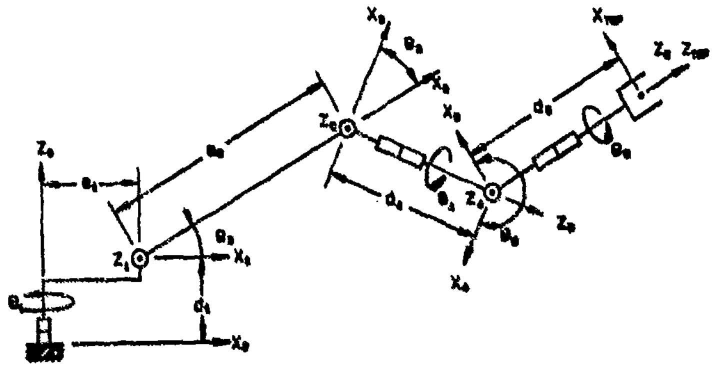

Figure 3. Kinematics of the ARMI.

Joint i	Twist Angle α_i (deg)	Offset Dist. a_i (in)	Link Length d_i (in)	Joint Angle θ_i (deg)
1	90	12	10	± 240
2	0	36	0	+ 135, -90
3	90	0	0	± 135
4	90	0	18	± 240
5	90	0	0	± 135
6	0	0	18	∞

Table 1. Denavit-Hartenberg Parameters of the ARMI.

Figure 4. The NASA/NBS Parallel Jaw Gripper with an Electric Actuator.

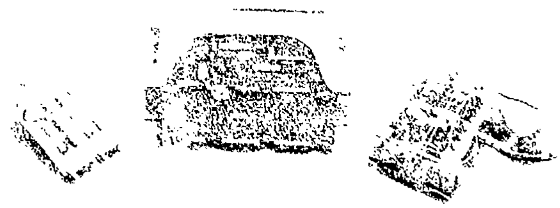

Figure 5. Universal Motor Controller Components.

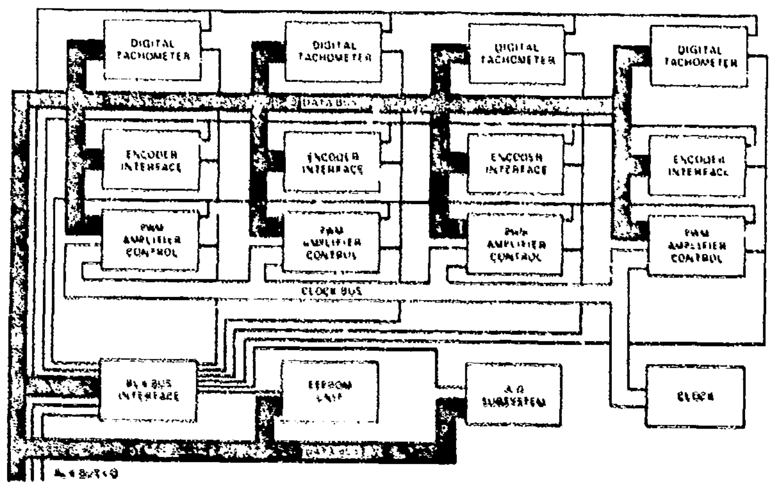

Figure 6. Functional Block Diagram of the UMC Joint Controller Card [7,8].

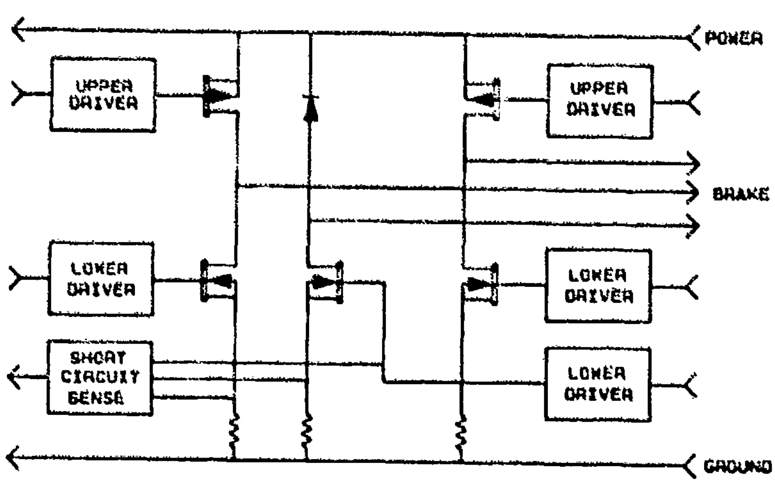

Figure 7. Block Diagram of the UMC Pulse Width Modulated Power Amplifier [7,8].

Figure 8. The DFVLR Steering Ball.

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Investigation of Learning Factors in the Performance of Teleoperated Tasks

by

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ABSTRACT

Recent work conducted at the University of Alabama in Huntsville has investigated the learning involved in the repeated performance of simple teleoperation tasks. The experiment used a simple peg-in-hole task to compare a 2 second delay operation mode with the no delay mode. The results clearly show the differences in learning between the two cases and provide an indication of the learning patterns experienced.

INTRODUCTION

The high costs of teleoperated system operation in space, military, or hazardous environments is focusing increased research emphasis on the training aspect of system operation. For example, control of many space based teleoperated systems will be accomplished through the use of expensive satellite transmissions. Operator induced delays in this type of situation can quickly cause schedule slips and other delays that will incur significant expense. Similar types of operation expenses exist in other fields, and the expense of training equipment and facilities for these operations will be justified.

A pronounced learning effect is perhaps most apparent in time delay situations. Time delay is common in space related telerobotic operation due to the transmission delays experienced. The "move-and-wait" strategy is often noted in time delay research, and as operators become more familiar with the equipment and the task, they begin to combine moves [1]. All factors of the learning involved in performing teleoperated tasks influence the method of training and the approach taken in the development of teleoperated tasks.

A survey of previous teleoperated robotics experiments indicated that some patterns could exist in the learning process for time delay teleoperation. The purpose of this experiment was to evaluate two theories. First, an effort was made to determine if there exist any noticeable patterns in the learning process for either a time delay or no time delay teleoperated task. Second, the learning factors for both the time delay and no time delay cases were compared in order to determine if any significant differences in learning patterns were observed.

EXPERIMENT

In order to analyze the theories noted above, it was necessary to develop an experiment which could satisfy the following parameters:

- Multiple repetitions per operator.
- Simple format.
- No complex manipulations requiring extensive training.
- Minimum subject time required (approximately 1 hour each) since the subjects used were unpaid.

The experiment used in this study was a simple peg-in-hole type procedure. This type of experiment was chosen since it could be performed by operators with little training and since the duration of the experiment was short enough to lend itself to multiple trials in one session without leading to noticeable operator fatigue. The experiment consisted of each subject performing five trials of the simple task. If an equipment malfunction was noted, the trial was repeated.

EQUIPMENT SET-UP

The experiment was performed in the Telerobotics Laboratory of the Johnson Research Center at the University of Alabama in Huntsville. The laboratory is equipped with a Puma 562 6 degree of freedom robot arm. The arm is remotely operated by two 3 degree of freedom joystick/paddle type controllers. The intermeshing gripper used in this experiment was operated by a toggle switch located at the operator station. A task board donated by the NASA Marshall Space Flight Center was used as the focal point of the experiment. This board is equipped with the necessary fixtures to perform several types of peg-in-hole experiments as well as other types of experiments such as electrical connectivity and simple latch manipulations.

Four cameras were used in this experiment. Three of the cameras were high resolution black and white cameras. The first black and white camera was positioned directly on the robot arm. A second black and white camera was mounted on a tripod at the height and to the left of the task area. The third black and white camera was positioned to the right of the task area and behind the position of the robot arm. The fourth camera used in this experiment was a medium resolution color camera. This camera was placed to the left of the task area and behind the position of the robot arm. The color camera is equipped with pan/tilt/zoom capabilities, and these features were available to the operators during the experiment if they so desired. Lighting for the experiment was provided by a set of four 600 watt quartz lights mounted on tripods.

The operator station is equipped with four monitors. Three 9 inch black and white monitors are positioned in a row directly at operator eye level. A 13 inch color monitor was positioned directly under the black and white monitors. The robot controllers were positioned directly in the center of the operator station and directly at hand level. The gripper controller and color camera pan/tilt/zoom controls were positioned to the right of the color monitor but well within convenient reach of the operators.

The experiment consisted of two cases: (1) performance of 5 trials in a "real time" (no time delay) situation, and (2) performance of 5 trials in a 2 second delay mode. The delay was induced using a software program developed at the UAH Johnson Research Center. The delay program is used to simulate the transmission delays that will occur in space based telerobotics operations. Six subjects performed the no delay experiment. Four subjects performed the 2 second delay experiment.

ANALYSIS OF DATA

Each of the five trials performed by the subjects was plotted in order to observe the difference between progressive trials. From this analysis, it was noted that each of the subjects performed his/her shortest task time on the fifth trial with one exception. Six out of the ten subjects experienced their longest time on their first trial. The data proved as expected, and in general, the more trials run the less time required to complete the task. Upon further analysis, the following observations were made:

Subject's Average Task Completion Times

The average time readings for each subject in the 0 second and 2 second delay experiments are presented in Figures 1 and 2, respectively. These figures display a range of subject times, and the difference in magnitude of the times between the two graphs indicates the increased level of difficulty of the time delay operation.

Overall Average of 0 Second Delay vs. 2 Second Delay Times

Figure 3 presents a comparison of the overall average times for the two experiments. This graph confirms the increased difficulty of the time delay operation. It is interesting to compare the relative slopes of the two lines. The slopes are comparable between time readings 1 and 2 and also between readings 3 and 5, but the slopes between readings 2 and 3 differ significantly. This is the point in the experiment where the peg is being positioned for insertion into the hole. This task is by far the most complex of the experiment and requires a series of very precise movements. The differing slopes indicate that precision tasks must be performed at a much slower rate in time delay operation.

Task Times as Functions of Repeated Runs

Figures 4 and 5 present the task times for both the 0 second and 2 second delay modes. These graphs are prepared using the subject's completion times for each of the 5 trials as data points, and both cases clearly show that task completion time reduced considerably over the course of the 5 trials. The learning effect is especially noticeable since the subjects had only minimal exposure to the equipment prior to the experiment.

Average Task Time as a Function of Repeated Runs

The data presented in Figure 6 show the learning factor over the 5 trials. It is interesting to note the differences in magnitude of Run 1 and Run 5 times between the two cases. The 0 second delay line shows a decrease of approximately 2 minutes in total time, while the 2 second delay line shows a difference of approximately 3 minutes in total time. Although the magnitudes differ substantially, the relative differences are quite similar.

FIGURE 1. AVG. FOR EACH ZERO SECOND TIME DELAY SUBJECT

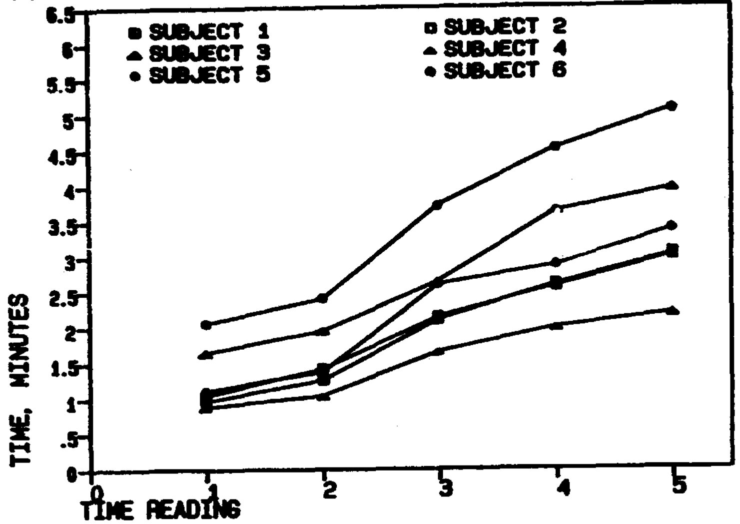


FIGURE 2. AVG. FOR EACH TWO SECOND TIME DELAY SUBJECT

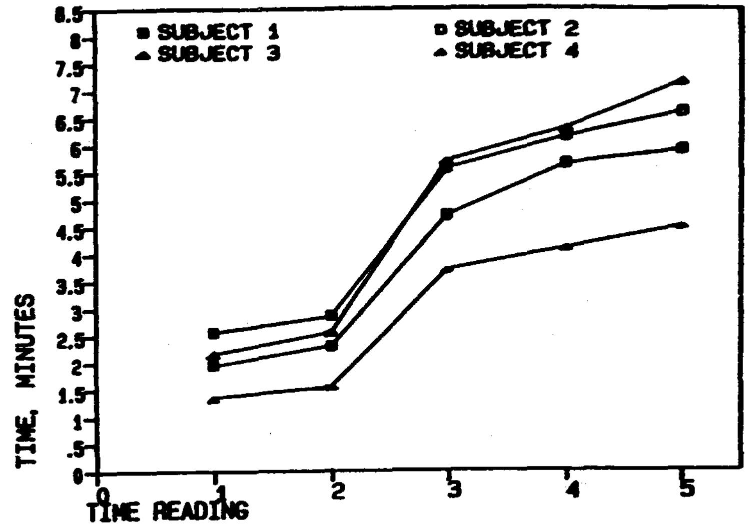


FIGURE 3. AVG. OF ZERO SEC. DELAY VS AVG. OF TWO SEC DELAY

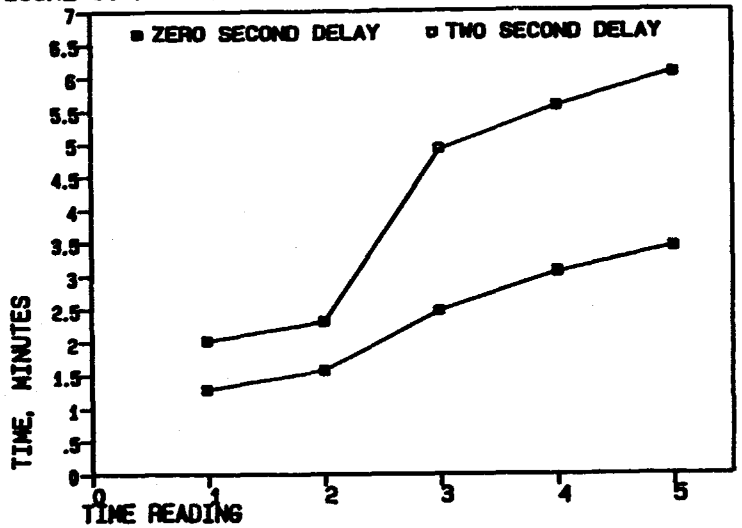


FIGURE 4. TASK TIME AS A FUNCTION OF REPEATED RUNS (0 SEC)

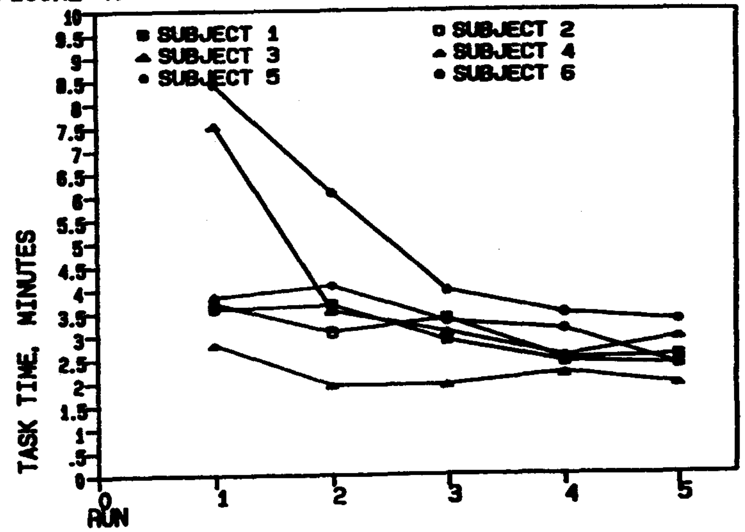


FIGURE 5. TASK TIME AS A FUNCTION OF REPEATED RUNS (2 SEC)

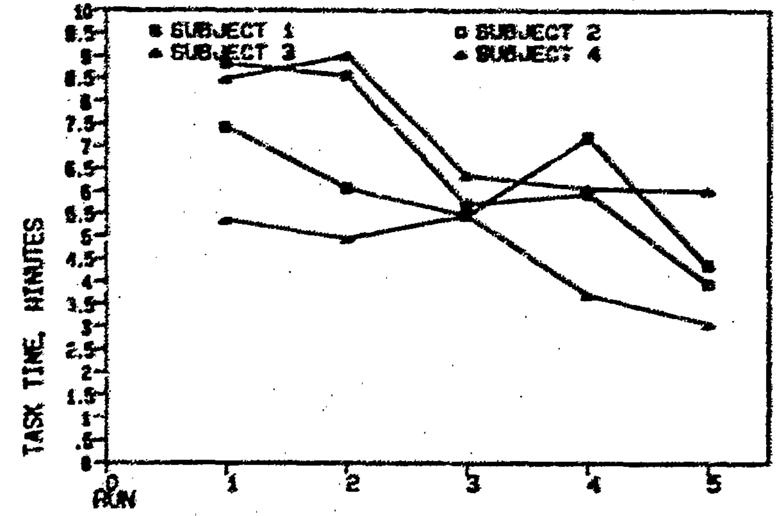


FIGURE 6. AVG. TASK TIME AS A FUNCTION OF REPEATED RUNS

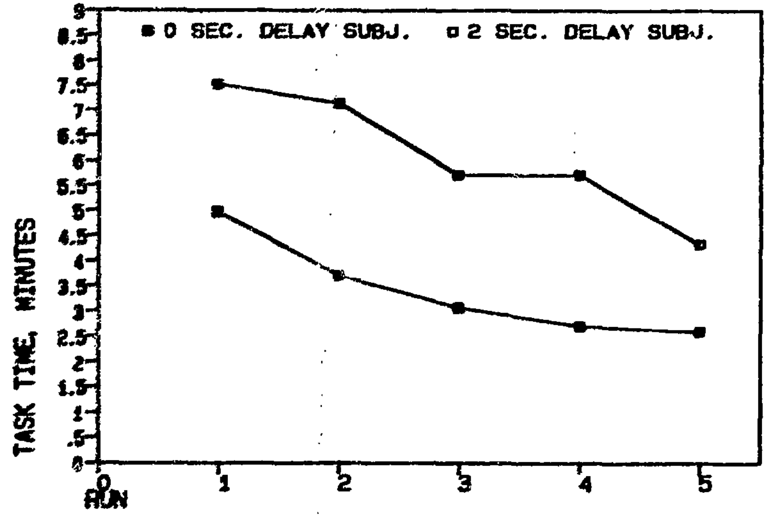


FIGURE 7. LEARNING COMPARISON FOR ZERO SECOND DELAY

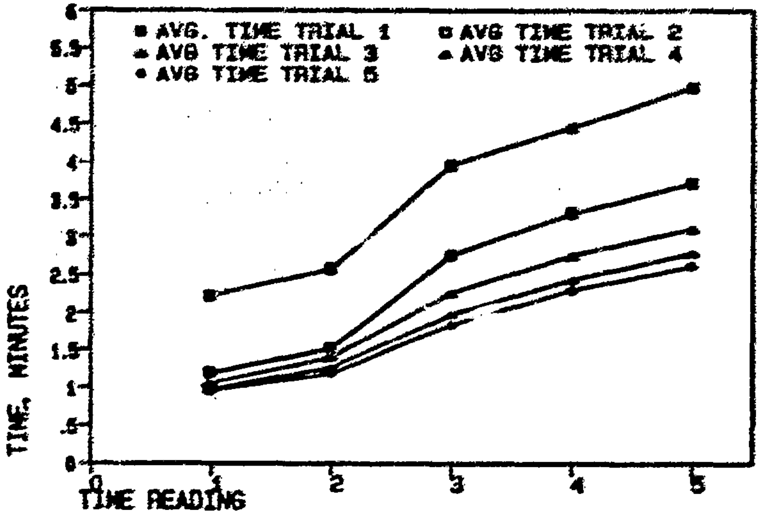
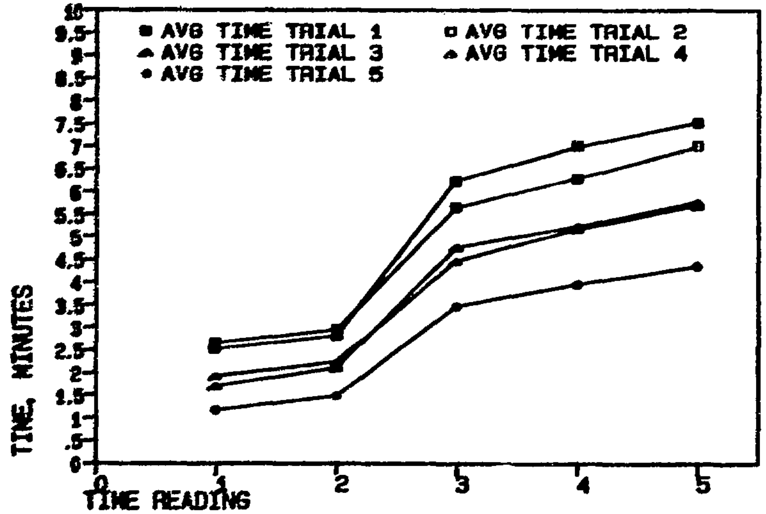


FIGURE 8. LEARNING COMPARISON FOR TWO SECOND DELAY



Learning Comparisons for 0 and 2 Second Delays

Learning comparison graphs are presented for both cases in Figures 7 and 8. The 0 second delay case (Figure 7) clearly shows learning involved in each trial. The times for each subsequent trial are reduced, but the magnitude of reduction is sharply lower over the last three trials. This result indicates that in a no delay environment, the learning effect for simple tasks can be minimized in only a few trials. Also of interest is the reduction in slope between time readings 2 and 3 that occurs over the 5 trials. This result indicates that for no delay situations, significant learning occurs in tasks of varying complexity.

Figure 8 presents a learning comparison for the 2 second delay subjects. This graph also shows significant learning over the 5 trials, but the relative magnitudes of the differences between lines indicate that the magnitude of learning has not significantly decreased after 5 trials. This result indicates that in order to minimize the effects of learning in a time delay situation, a longer period of operator training will be required. Further observation of this graph shows that the slopes between time readings 2 and 3 decreased at a much slower rate. This result indicates that the learning effect for more complex operations may not be as great (and is certainly evidenced at a slower rate) as the learning effects for similar tasks in a no delay operation mode.

CONCLUSIONS

The results of this experiment clearly show that significant learning is involved even in the performance of simple teleoperated tasks. The differences in the results for the two cases show that additional training will be required for time delay operation in order to achieve a level of competence similar to that of no delay operation. Additional research with more complex tasks in time delay modes will help define the parameters of the learning process, and these results can then be used to help develop training programs and algorithms to predict the time required to perform teleoperated tasks for time delay operations.

The field of human factors will continue to provide important contributions to the development of efficient and cost effective teleoperated systems. Research into the ergonomic and environmental aspects of human controlled teleoperation will provide the basis for the development of operator environments which will maximize operator performance while minimizing discomfort and fatigue, and continued investigation of operator performance will lead to more efficient work design and task planning.

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Session VI Program B

Manufacturing of Aerospace and Military Systems II

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Development of Automation & Robotics for Space via Computer Graphic Simulation Methods

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Abstract

The development of advanced automation & robotics (A & R) for space and earth based systems requires that critical hardware and software issues be resolved. Robotic mechanisms must be controllable and have kinematics designs, dynamic characteristics, end-effectors and working environments correctly designed for their tasks. Software systems must be capable of controlling these mechanisms in a timely manner and adapting to operational changes, while telerobotic systems must also have user interfaces that optimize the human's ability to plan and control operations. This papers describes the use of ROBOSIM, a robot simulation system, to perform several A & R system design studies.

Using ROBOSIM, a model of the robotic mechanism is built via a procedure-oriented solid modeling language. The simulator generates the kinematics, inverse kinematics, dynamics, control and real-time graphic simulations used to study the arm's performance. Robotic control algorithms, path-planners or teleoperator control stations may be evaluated by an interface allowing these systems to control the simulated robotic mechanisms. ROBOSIM was developed over a three year period and in the two years since it became operational it has been applied to the design of robotic systems used in earth-based manufacturing and to evaluate space-borne robotic systems.

1. Introduction

Robotic systems have become increasingly important to all facets of manufacturing: space is no exception. Perhaps the most publicized space robot is the Remote Manipulator System (RMS) which was built by Canada for the U.S. Space Shuttle. Prior to the RMS, robot manipulators were used on unmanned spacecraft to investigate soil properties on the moon and on Mars. Plans for the U.S. Space Station which will become operational in the early 1990's include the use of teleoperators and robots to perform routine station tasks e.g., inspection and maintenance. Earth-bound robots have also been used extensively to support the manufacturing (Refs. 1,2) of spacecraft components. Although the applications for space and earth seem radically different there remain many common issues in the procedures for design and testing of robot systems. Graphic simulation has proven to be extremely effective in the design of both types of system. In this paper we will examine: design issues for tele-robotic systems; ROBOSIM, a NASA developed computer graphic simulation tool; and simulations of tele-robotic systems for the Space Station and the Orbital Maneuvering Vehicle.

Kinematic Design Issues

In designing a robotic application the selection of the robot's kinematic design is usually considered first. The number of robot joints, the type of joint (revolute or prismatic), and the physical configuration of each jointed segment are all elements of the robot's kinematic design. The position of the last reference frame (hand frame) is determined by the joint positions and the geometric relationships (kinematics). Minor changes in the kinematic design of a manipulator can greatly affect the volume through which the robot's hand may be moved. The design of the end-effector (tool) and the orientation of the part (workpiece) with respect to the robot (part positioning) also greatly affect the ability of a robot to perform a given task. For applications which will use an existing robot the designer must choose the appropriate robot, design the workcell layout and part fixturing. For systems which will use a custom-built robot, the task of designing the robot is added. A mistake in the design of a cell without the use of computer graphic simulation may not be detected until the hardware integration phase. This can result in costly schedule delays, procurement of incorrect components, and a greatly increased system cost.

Robot Motion Control

Robot control development is another area which can benefit from the use of computer graphic simulation techniques. Robot control algorithms may be viewed as existing at two levels: the kinematic control level; and the path planning level. Kinematic control algorithms are a function of the arm's kinematic design. These algorithms relate the position of the end-effector's reference frame to the joint position commands required to achieve the commanded position. These algorithms are a software implementation of the inverse kinematic equations. Prior to the use of graphic simulation, the control programs were debugged by observing the robot's motion subject to the commands of the experimental computer program. For robot systems with relatively low lifting capacity, a faulty program resulted in little more than embarrassment for the developer, however robot capacities have increased to the point where payloads are in the hundreds or thousands of pounds. Mistakes in programming can be serious. Another difficulty encountered in using the actual mechanism in the debugging process occurs for robots designed for use in zero-G which may not operate in a one-G environment. Again graphic simulation is the indicated procedure for this type of development.

Robot Path-Planning/Verification

Robot path-planning is the process of developing the sequential position, orientation and velocity commands that the robot's end-effector must execute in order to perform the desired function. Most current industrial robots are programmed using a teach pendant to manually command the robot to the desired points, this is the on-line manual programming method. Manual programming is highly in-efficient since the robot must be taken out of service, the path generated manually, replayed for verification and ultimately executed. On robots whose path programming is changed infrequently this is not significant, but for systems in which programming must be flexible manual programming is not satisfactory. Just as numerically controlled (NC) machine tools have become entirely programmed by off-line algorithms, the programming of robots will also eventually all be automated. Graphic simulation is a vital step that must be performed prior to the execution of an off-line generated robotic path program. Simulation will verify that: (1) the path specified is correct for the task; (2) the inverse kinematic equation may be solved at all points along the path program (controllability); and (3) the arm or other components will not collide accidentally with obstacles within the workcell.

Tele-robotic systems, similar to those planned for space operations, have an additional path control mode which utilizes a human in the control loop to perform motion control in response to visual feedback from camera systems. Since the planning of the manipulation task occurs essentially in real-time, it is important to provide a means of rehearsing the planned operations. Rehearsal on a computer graphic simulator will allow the human operator to anticipate problems that may occur e.g., obstacles obstructing motion or viewing and singularity conditions in the motion control software. In real-time, the computer graphic simulation may provide an additional "view" of the task from another direction to aid in obstacle avoidance.

Robot Dynamics

In industrial applications the primary dynamics issues are that the robot chosen for a task is capable of handling the required payload weights and transport velocities. Industrial robots are typically rated for lifting capacity only. An approximation of the robot's ability to perform a task dynamically can be made through dynamic simulation of the loaded robot. The maximum joint loads recorded during the dynamic simulation are compared to the loads that result if the manipulator were statically loaded per the manufacturer's specifications. If these joint loads are exceeded by the dynamic tests, then the robot may not be capable of performing the task. Since this is only an approximation, a safety margin should be used in making the final decision.

Although dynamic simulation is important for industrial robot systems, it is mandatory for systems used in space. Manipulator mechanisms and joint actuators are limited in weight due to launch considerations. Power supply limits reduce the size and rating of the mechanism's actuators. Dynamic studies will help to insure that the planned robotic tasks do not exceed the limits of the mechanism. The zero-G environment may be an advantage for handling larger payloads than would be possible on earth, but the dynamic interactions of the loaded manipulator and its mounting platform are significant for a space based robotic system. The possibility exists for parasitic oscillations to occur between the manipulator and the spacecraft's attitude control system. Simulation studies may reveal the existence of these or other undesirable effects.

2. ROBOSIM Overview

Simulation Procedure

ROBOSIM was developed over a three year period at the Marshall Space Flight Center (MSFC) to facilitate the design and development of robotic systems. Prior to ROBOSIM, robotic simulations were limited to the construction of scale models. Using ROBOSIM the kinematic design of the manipulator mechanism and other workcell components are modelled via a simulation language. The model consists of solid primitive shapes which approximate the robot's shape and mass properties. The joint configuration and type, either revolute, prismatic or fixed, are also specified. Once modelled, ROBOSIM computes the standard linkage (Ref. 3) parameters, the inverse kinematics and the manipulator's dynamics. The designer may also specify the joint actuator transfer functions. Path motion is specified by position and velocity language constructs.

ROBOSIM Hardware Configuration

ROBOSIM is resident on a Digital Equipment Corporation (DEC) VAX11/780 processor. During simulation development the user may use a low cost terminal with TEK 4014 graphics compatibility. Although a simulation may be executed using a non-real-time terminal, the use of a real-time graphics display is preferred. Interfaces have been provided for several dynamic display systems including Evans & Sutherland PS330, GTI Poly 2000, Silicon Graphics IRIS with other interfaces planned. A limited Initial Graphics Exchange Standard (IGES) pre- and post-processor allows ROBOSIM to communicate graphics and tool motion commands with any CAD/CAM system adhering to the standard which was developed by the U.S. National Bureau of Standards.

The simulator's speed for non-dynamic studies is greater than real-time. This speed is decreased for very large models with multiple robots or robots with many degrees-of-freedom. Studies that required the modelling of dynamic effects also load the simulation processor. An Applied Dynamics AD10 parallel processor is used to improve the simulator's response in these situations.

ROBOSIM Software System Structure

ROBOSIM's software structure may be characterized as a hierarchy of three levels of software utilities. This structure is typical of large software systems. At the core or kernel of this system are routines that provide support for the most rudimentary of simulation tasks. Included among these functions are vector and matrix arithmetic and display control. The typical user of ROBOSIM interacts with these routines indirectly through his use of higher level utilities. A characteristic of routines at this level is their inflexibility in their interfacing requirements i.e., data must be provided in specific formats. By interfacing via the higher levels a user avoids these requirements, however direct access is available when needed. Typically, a ROBOSIM user who is performing simulation studies involving externally supplied mechanism control algorithms must communicate directly with the kernel routines.

The second level within ROBOSIM integrates the lower level routines into more complex algorithms that perform often needed tasks in display management and robot control. Examples of graphics routines that function at this level include subroutines to perform viewpoint and perspective transformations. Examples of routines that service robot kinematics and control issues include those which perform end-effector position computations and formulations of the manipulator's Jacobian matrix.

The highest level within ROBOSIM provides the human interface. At this level robots, workpieces, and fixturing assemblies may be modelled, placed within a workcell, programmed, dynamically simulated and viewed using fewer than forty distinct language instructions. The simplicity of this software interface greatly increases ROBOSIM's use and it is this interface that is perhaps the most important feature of ROBOSIM.

3. Simulation Examples

ROBOSIM V1.0 became operational in July 1985. In the year since, ROBOSIM has been applied to several industrial robot systems. A discussion of this previous work (Refs. 4,5) is presented elsewhere. The simulations presented below are being implemented to facilitate the development of tele-robotic systems for on-orbit operations.

Simulation of the U.S. Space Station

The Space Station is the next major NASA program. The Space station will provide a permanent base from which NASA will be able to conduct experiments in manufacturing, science, medicine and earth resource management. Another important role for the Space Station will be as a base for the servicing of satellite systems. The U.S. has a considerable investment in orbiting assets and when projected future space systems become operational servicing and repair will become mandatory.

A computer graphic simulation of the Space Station using ROBOSIM is given in figure (1). In figure (1) we see the Station's growth configuration modelled. The Space Station structure is composed of a frame which will be assembled in space; two pair of large photo-electric solar panels for power generation; two pair of smaller heat exchanger panels; thermal concentrators (units with hexagonal elements); and the habitability/service modules (cylindrical elements). Although each cubic truss element measures (5) meters on a side, the entire structure is designed to be transported into orbit via the Space Shuttle for assembly in orbit. Computer graphic simulation will play an important role in the planning of assembly procedures. During the actual assembly, graphic simulation will be a useful tool to perform contingency studies in the event that problems arise during the planned assembly procedures.

Once operational, computer graphic simulation will facilitate robotic operations on-board the Space Station. Planning activities will be required to insure the co-operative handling of payloads being loaded or unloaded from the Space Shuttle. The problem of planning these activities is complicated by the constraints imposed on the orientation of the Space Station needed to control thermal radiation and power generation. Figure (1) depicts the Space Station in its orbit about the earth. The model is fully articulated so that the orientation of the Space Station and the resulting positions of the photo-electric panels, heat radiators, solar collectors and antennae may be simulated to determine the best time window for a tele-robotic operation. This window is chosen to optimize lighting conditions and minimize the likelihood of collisions between service elements and obstacles.

Since the success of teleoperation is also contingent on the ability of the human to view the task, graphic simulation will also be used to determine if the locations chosen for closed circuit TV cameras will provide an unobstructed view. Figure (2) was generated by placing ROBOSIM's viewing point at a common module simulating a view from on-board the Space Station. Multiple viewpoints will be useful for studying a variety of tele-robotic scenarios.

ROBOSIM's ability to perform dynamic simulations will be used to determine if the planned operations generate reaction forces on the Space Station's structures that would cause a disruption to experiments that are operating concurrently. If conflicts of this type are discovered, then alternative operations may be studied.

Typical satellite servicing missions to be supported by the Space Station will also include those in which a small free-flying vehicle will be used to rendezvous with satellites in high orbits e.g., geostationary orbits of 22000 miles. The next section describes a free-flying vehicle currently being developed by NASA and how its development will be assisted by computer graphic simulation.

Design of Tele-robotics for the Orbital Maneuvering Vehicle

The Orbital Maneuvering Vehicle is designed as a re-useable, remotely controlled, free-flying vehicle capable of performing a wide range of on-orbit services in support of orbiting assets. It is projected as an important element of the Space Transportation System (STS), designed to operate from either the Shuttle, the Space Station or from the ground. The descriptions of the OMV or manipulator mechanism contained in this paper are not specific to any designs which may be currently under consideration by the U.S. National Aeronautics and Space Administration, however, the functional concepts (Ref. 6) described are correct.

The concept of the OMV includes the ability to accept mission kits to allow it to perform a variety of tasks in addition to its role as recoverable booster. One such kit is a manipulator/teleoperator, the "Smart Front-End" (SFE), which will allow remotely controlled manipulation to accomplish satellite and Space Station service tasks on-orbit. Figure (3) illustrates this concept. The OMV is shown equipped with a generic SFE manipulator. The SFE pictured consists of a bilateral pair of six degree-of-freedom (DOF) manipulators and a manipulator transport mechanism. The transport system provides three DOF: a rotary track which encircles the docking adapter; a hinged boom; and a sliding joint allowing the bilateral pair to traverse the boom. The generic satellite which is being serviced in figure (3) is shown detached from the OMV/SFE cluster for clarity. In normal operation a solid connection would be established by a docking mechanism.

ROBOSIM will be used extensively to assist in the development and evaluation of concepts for the SFE manipulator. Kinematic studies will reveal whether the SFE mechanism can be folded and stored within the space allocated on-board the Space Shuttle. Other kinematic studies will be required to determine if the OMV/SFE cluster can be successfully deployed from the cargo bay by the Space Shuttle's RMS. In figure (4) our generic OMV/SFE cluster is shown with the SFE folded in the stowable configuration. Further kinematic studies will determine if collisions between the SFE manipulator and satellite appendages occur during the execution of planned motion paths.

The implementation of an SFE manipulator will also require the development of several modes of mechanism control. An algorithm to control the SFE during deployment or un-folding will be developed. Although this type of algorithm usually involves a predetermined sequence of joint motions, provision must be included to override this sequence, if necessary, and execute new motions to correct or avoid anomalies. During docking operations the mechanism can take a passive or an active role. If a passive role is assumed, control algorithms for the SFE can improve the maneuverability of the OMV by arranging the arm's configuration to minimize inertial imbalance, avoid obstruction of the target satellite and prevent the reaction control system (RCS) thruster plumes from impinging on the SFE. Strategies of controlled compliance in the SFE joint servo control loops may further improve the controllability of the OMV during fine docking maneuvers by decoupling the SFE's mass or actively using the SFE's momentum to affect additional control.

Once the OMV is docked with the target satellite a variety of different control issues must be resolved. As previously mentioned, algorithms that use mechanisms with kinematic redundancy to avoid collisions and minimize disturbance torques could significantly improve the system's performance. Real-time computer graphic simulation coupled to prototype teleoperator workstations can aid in resolving many issues relating to man-in-the-loop control. The placement of cameras may be simulated to insure that the field-of-view (FOV) is not obstructed. If a dual arm SFE design is chosen, graphic simulation could help to determine the most effective human interface for controlling the bilateral mechanism. Graphic simulation will not end with the successful SFE design, during servicing activities, a graphic display will allow the human operator to preview service tasks in simulation. Since communication delays in the man-in-the-loop control system may be large and varying, the use of a "predictive graphic display" to supplement the delayed visual feedback may improve the efficiency in performing operations remotely. When semi-autonomous or "supervisor control" methods are developed, the graphics display would allow the human to verify mechanism motions that are proposed by the controller. One final note relates to the design of the satellite rather than the OMV itself. Current satellite design philosophy is oriented toward multiple redundancy and no post-launch servicing, the advent of on-orbit service techniques will relax some of these design constraints, but satellite design must change to take advantage of these new possibilities. Hardware simulations (Refs. 7-11) of servicing missions on modular satellites have been performed, but computer graphic simulation provides a cost-effective means of preliminary evaluation of the compatibility between a satellite and the servicer.

4. Conclusions

The experience gained at the Marshall Space Flight Center indicates that the use of computer graphic simulation in support of tele-robot systems development is extremely important. Although hardware simulation is not replaced by these computer graphic simulators, a considerable cost savings is experienced by delaying hardware implementation until the designs have matured. Once a robot system becomes operational the value of graphic simulation continues as a means of previewing planned task execution. It is expected that as the performance of computer graphic simulators increases and as hardware costs decrease the use of graphic methods will become widespread.

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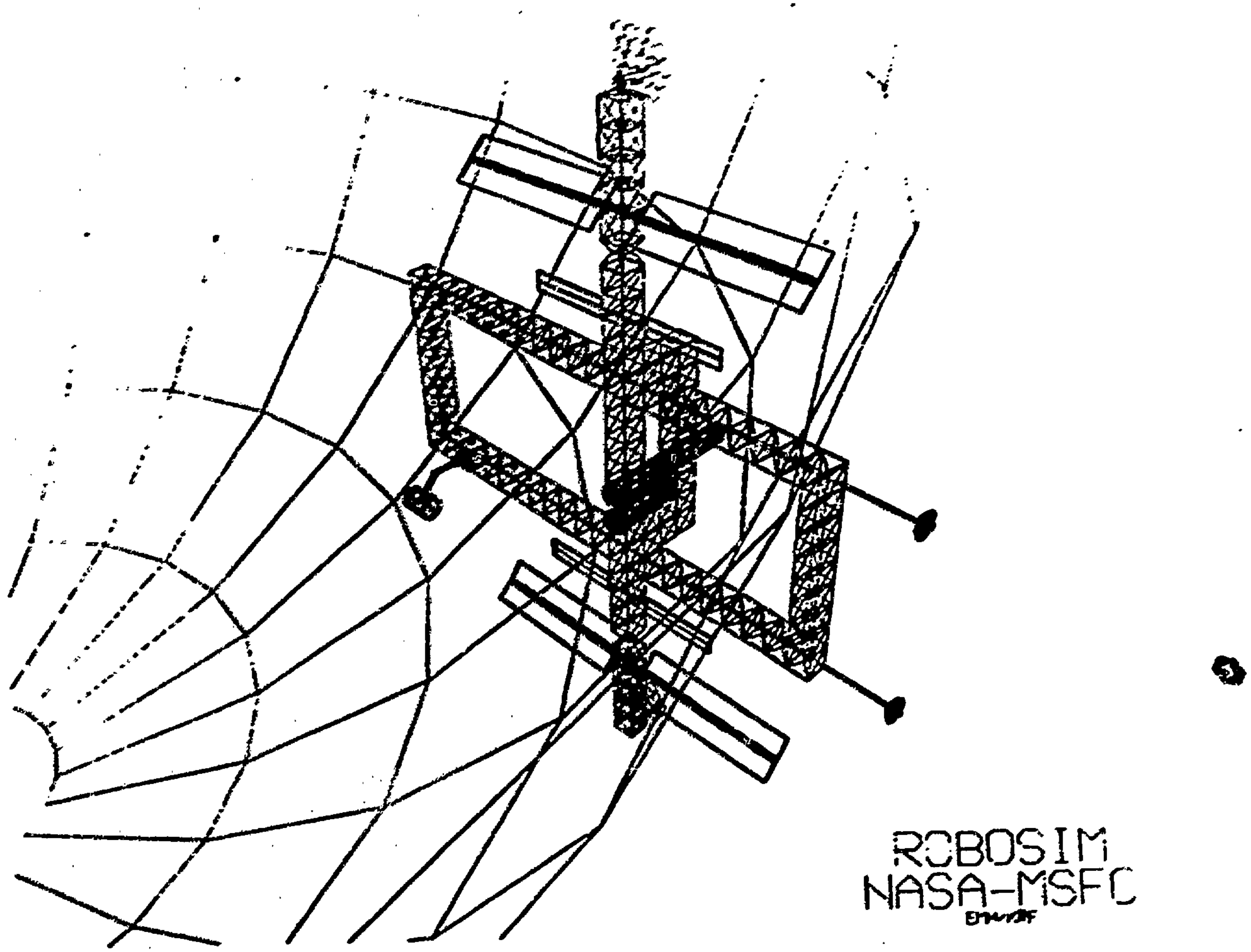

Figure 1. U.S. Space Station Growth Configuration Model

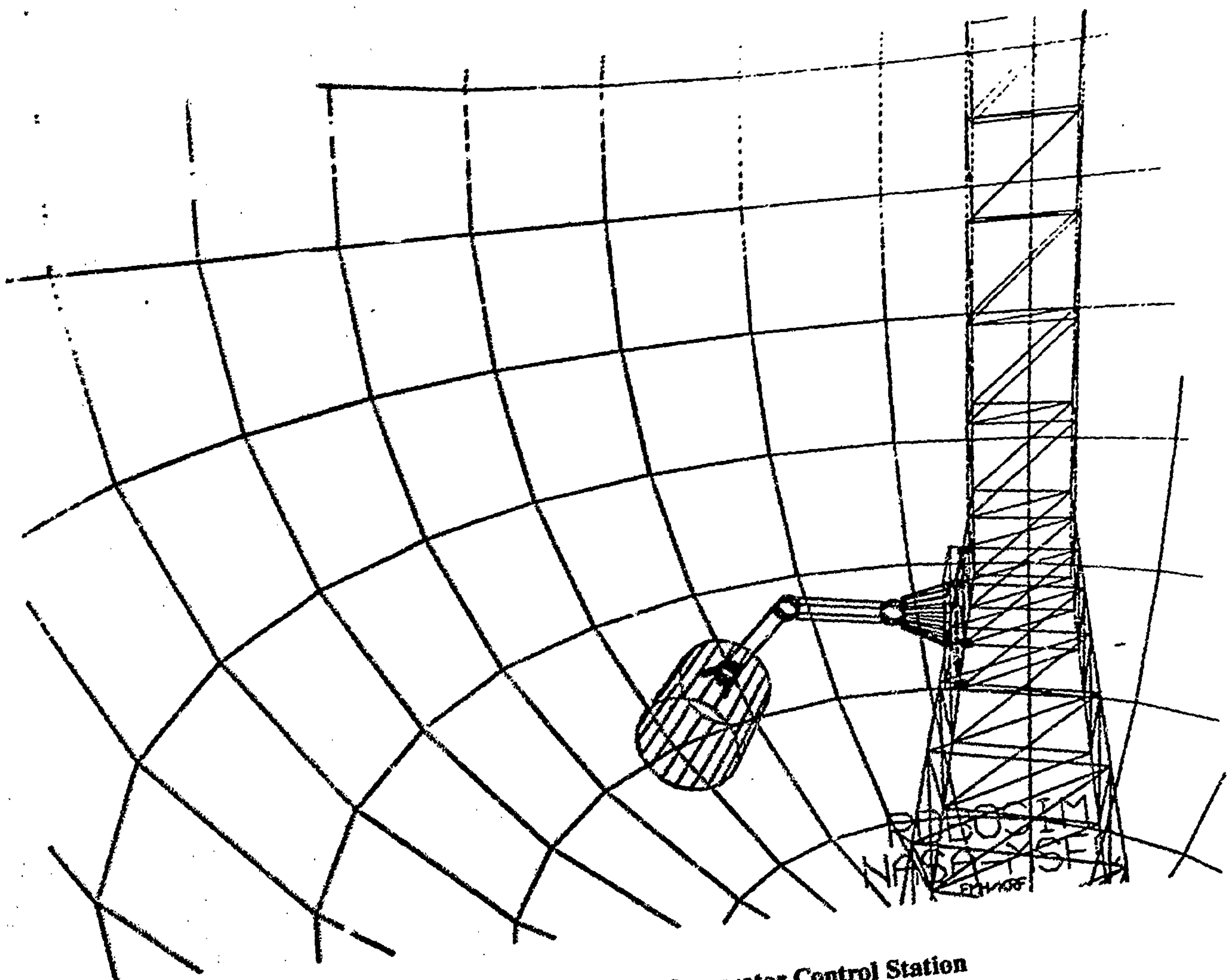

Figure 2. Simulated View from Teleoperator Control Station

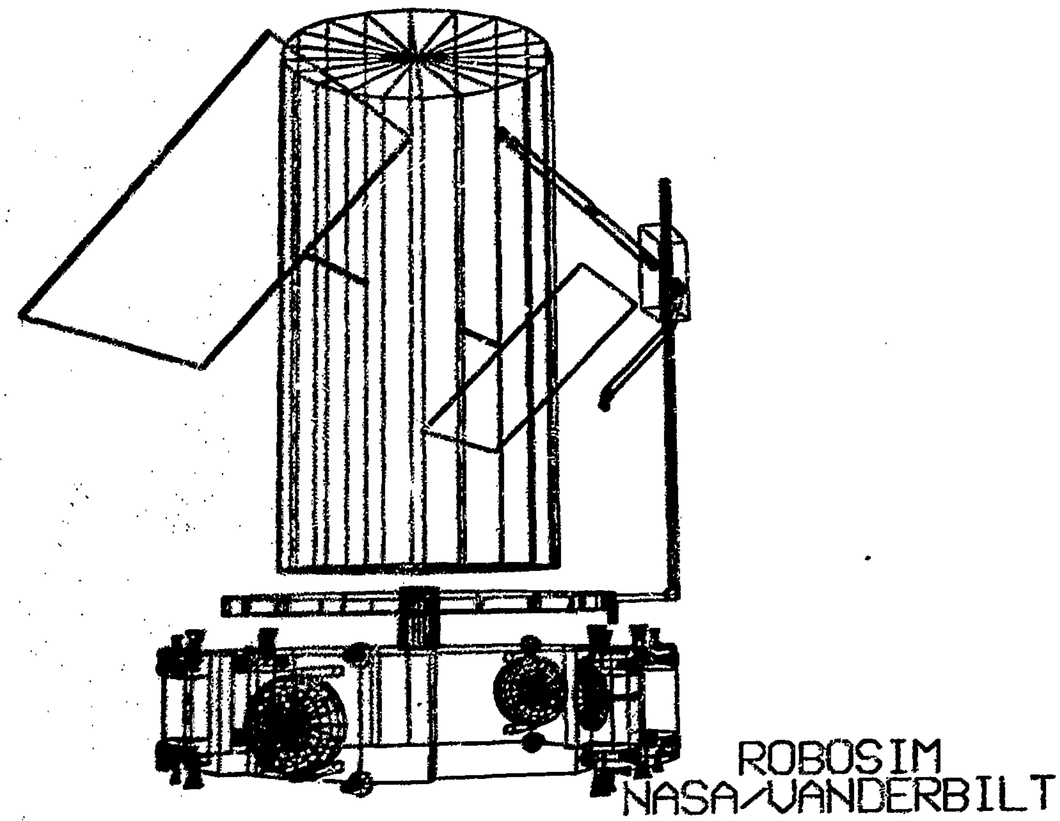

Figure 3. Orbital Maneuvering Vehicle Performing Satellite Servicing Mission

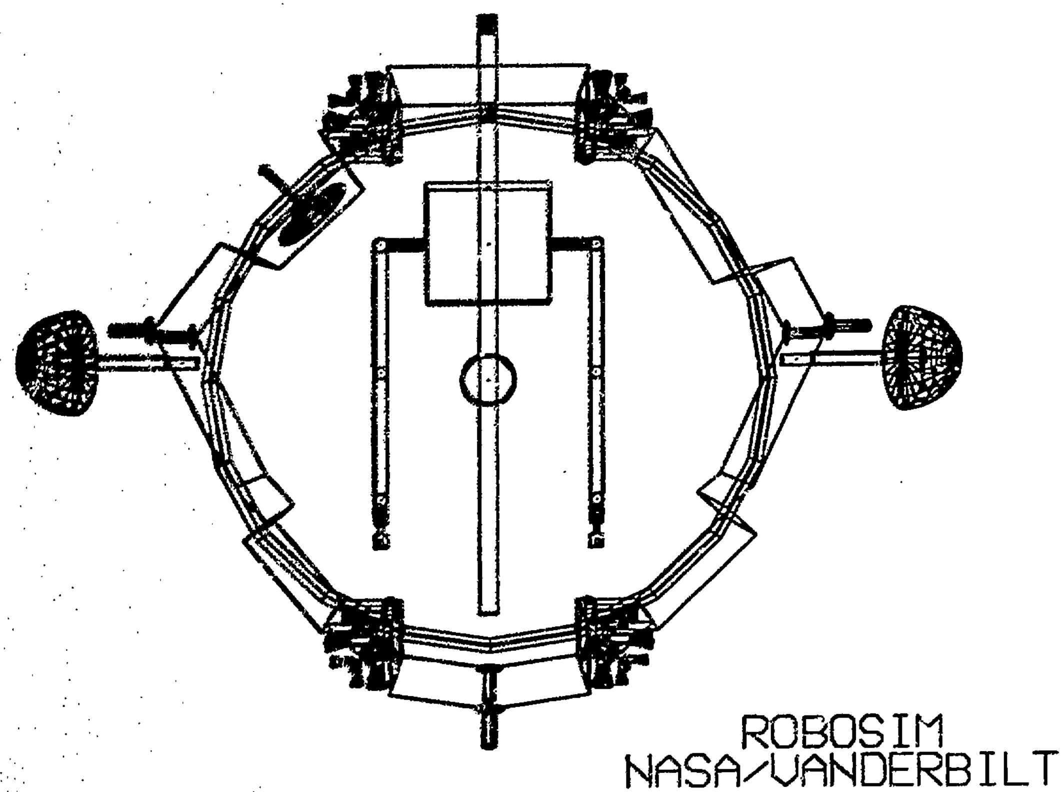

Figure 4. Satellite Servicing Mechanism in Stowed Position

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On Designing A Case-Based System for Expert Process Development

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ABSTRACT

In artificial intelligence literature, using prior experience to help solve new problem situations is termed "case-based" reasoning. Various authors have proposed using case-based reasoning for learning new concepts in mathematics, for clinical problem solving, for settling legal issues based on common law, and for interpreting and resolving common sense disputes. This paper discusses the need for such reasoning in performing process development tasks. In particular, it describes the significance of compiling case histories to capture critical process knowledge and the methods of compiling and reasoning with such histories to reduce process development time and enhance its reliability. This approach is especially useful in situations where existing processes are modified in response to frequent product changes or when processes developed for a prototype operation have to be ported to production systems.

A system to explore such ideas has been designed and is under implementation at Martin Marietta to assist process engineers and technicians in evaluating the processability and moldability of poly-isocyanurate (PIR) chemical formulations for the thermal protection of the Space Shuttle External Tank. The Process Development Advisor (PDA) aids the process engineer in (1) identifying a startup set of process parameter windows from case histories of similar chemical formulations and their moldability in test mold configurations, and (2) refining these windows by diagnosing specific process problems and suggesting adjustments for fine tuning the formulations and/or machine and model setup parameters.

The PDA is composed of six different modules: a database manager, an experimental design module, a study module, a case memory unit, a control program and a user interface.

The data base manager is used for representing and organizing numeric sensor data in the form of tables and records as they are acquired from different experimental runs of the process. The experiment design module uses all of the known process parameters and properties of interest as input and recommends an optimal experimental design matrix for evaluating the effect of the parameters on the process. It evaluates the results of the experiments for individual and interaction effects and suggests a list of critical parameters for detailed study. The study module allows detailed characterization of a process by

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deriving empirical models of parameter-property relationships which are important for identifying optimum process windows. The functional relationship between the parameters and properties is an example of a model represented within the case history of a process.

The case memory unit is an episodic memory which stores case histories of past process development efforts organized in the form of MOPs (memory organization packets) and sub-MOPs. Individual events can be retrieved from case histories by approaching an appropriate contextual category of MOPs then indexing with the relevant MOP to derive information relevant to the current process development tasks. The control program is organized in the form of generalized process function schemas. Some schemas generate the appropriate context for case retrieval while others perform the necessary refinements to the retrieved models. Graphical representation of empirical models in the form of 2-D curve plots and 3-D surface plots as well as the intermediate results and final recommendations for the optimum process windows are accessible through the user interface.

Process knowledge is acquired by the system in the form of case histories. A case history is a collection of process development events represented in MOP form which consists of a context frame and a set of indices. The context frame contains information about the features (norms) that are common to all the events and sub-MOPs that are indexed under it. The indices are the characteristic features (differences) that distinguish between the events. Each MOP is a generalization of process behavior at some level of abstraction.

A case history starts with a basic set of ingredients in a chemical formulation and a corresponding set of in-process and post-process behaviors as its norms. The behaviors are modeled empirically in bottom-up fashion. To begin with, one starts with the experimental design module for the identification of process-critical variables. Then, one follows by the acquisition and organization of experimental data with the database manager. Finally, one concludes with the modeling of the relevant parameter property relationships with the study module. The study module also uses these relationships to generate optimum process windows for effective process control. Any changes that are made to the base chemical formulation to study the effect on process behavior are indexed by their differences from the norm with the MOP. For example, if the effects of a different catalyst on the process behavior have been investigated, then this event is indexed by such a difference and resulting models are stored under that index. The case memory is self-organizing in the sense that strives to minimize the search effort for the retrieval of relevant cases. It accomplishes this by identifying similarities between indices in terms of the order (first order, second order, logarithmic, etc.) of the property response models and merging them into generalized sub-MOPs, when possible. Thus, the norms of the newly created sub-MOP contain models that are applicable to a collection of events rather than to a single event. Such generalization improves the efficiency of storage as well as retrieval. Current implementation has a variable threshold on the minimum number of similar cases that would be necessary to generalize events.

The system's reasoning mechanism is guided by the control program, which consists of several process development schemas which are instantiated by a combination of input from the user and knowledge retrieved from the case memory. Typical examples of schemas are porting schemas, which contain knowledge about how to port models developed from one machine to another machine of similar make; scaling schemas, which contain information on how to scale models from a prototype operation to a production system; and characterization schemas, which contain information on how to develop a new process from conception if no relevant cases are found in the case memory.

For example, a process engineer may want to investigate the performance of a PIR polymer for use in a processing system that imparts more mixing energy than the prototype system. The PDA is given both the component description of the polymer and the distinguishing features of the target system and is asked to recommend the best startup set of process parameters that would optimize reactivity.

The PDA will first try to locate an identical case in searching through both contextual categories (MOPs) or PIR polymers and an index of mixing energy contained within. If one is found, the models under that index are transmitted to the porting schemas, which determine the optimum process window and report it to the user. If, on the other hand, the exact index is not found in the MOPs, the system reasons with the knowledge that two PIR polymers having the same polyols and catalysts but supplied with different mixing energies differ only in absolute reactivities and not in the model (first order, second order, logarithmic, etc.) employed for approximating their reactivities. It thus retrieves a model from the case history of a PIR polymer that shares the same polyols and catalysts. In this case the model is transmitted to the scaling schemas, which will recommend a minimal set of experiments (i.e., two experiments if a linear model is retrieved) to adjust the model by a scale factor. Any further refinement for optimum windows will again be handled by the porting schemas as discussed earlier.

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Expert System Technology: an Avenue to an Intelligent Weld Process Control System

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Abstract

This paper examines the problems in applying automation to arc welding for small batch size operations, and proposes a practical adaptive control model. It identifies two elements as principal to the model: sensor fusion and expert systems. Sensor fusion provides an interpretation of the weld execution environment. The expert system accesses this interpretation, as well as a rule base, to arbitrate among conflicting goals, such as cost and productivity. This is accomplished using a goal reduction strategy. In order to give the model a broad base of applicability, a generic approach is taken. System development is phased in a set of steps to minimize the redundancy of effort in applying the system to new welds, welding applications, or weld processes. These steps include generic engineering, weld process engineering (e.g. SAW, GMAW, and GTAW), and application engineering. This is supported by partitioning the system into components amenable to tailoring it for the broadest possible application. These components include the process engineering laboratory, application engineering laboratory, and the field location set-up. This partitioning supports iterative development of successive weld processes and applications, and provides a functional, maintainable architecture for the system.

Introduction

Small batch operations comprise an important segment of arc welding activity. In particular, this includes almost all welding done in Naval shipyards. Tasks such as these, because they are often costly, difficult, and hazardous, are desirable candidates for automation. Unfortunately, successful attempts in arc welding automation have been largely confined to repetitive tasks of large batch size (refs 1,2,3). Only limited success has been reported for automation of small batch sizes (refs 4,5).

The difficulty in applying automation to small batch arc welding operations lies in overcoming anomalies associated with machine, workpiece, and metallurgical variables attendant to the arc welding process. Such anomalies are common in Naval shipyard welding. Because of the low volume and massive size of vessel components, the tooling required to fixture and locate these subassemblies within tolerance is costly and difficult. Manual grinding operations prior to welding and distortions that develop during welding produce dimensional variations requiring compensation in torch position and process parameters. The key to resolving these difficulties, it appears, lies in applying an adaptive control strategy to arc weld operations.

Our investigation of adaptive control strategies for small batch arc welding suggests two elements are important to successful automation: sensor fusion and expert systems. Sensor fusion is necessary because no single sensor is sufficient for a reliable interpretation of weld progress. By combining the input of two or more sources, sensor fusion derives an intelligent picture of events transpiring in the target environment. The expert system provides the mechanism for making decisions based on this interpretation; it uses sensor fusion output in conjunction with a rule base to reconcile competing goals, such as cost, quality, and productivity, to make effective decisions during arc-on time.

The practicality of such a system depends ultimately on our ability to apply the system to an ever increasing variety of weld problems. We have therefore placed great importance on developing a generic approach to arc weld automation. We believe we have successfully determined and modeled this generic control system structure. This system, called the Naval Expert Welding Control System (NEWCS), is the focus of this paper. While the primary focus of our research has been on Naval shipyard applications, the system emerging from this research is applicable to a broad range of advanced programs.

GDI is developing the NEWCS as an expert adjunct to its conventional commercial welding control systems. We believe such a combination of conventional algorithmic control, augmented with an expert adjunct, will offer a low risk path to fully removing the human operator from moment-to-moment control of welding.

Operational and maintenance difficulties arise in systems which evolve by tacking together a miscellany of separately developed subsystems, derived from a variety of sources and based on differing design practices. To avoid these difficulties, we are developing the conventional control system and its expert adjunct as a fully integrated, consistent whole, using standardized methods and practices. By this means we expect to provide a complete set of capabilities, fully integrated, without the "patchwork quilt" appearance and behavior of so many of today's welding control products.

Expert Systems

Expert systems are computer programs that use the knowledge underlying human expertise to solve difficult problems. This knowledge is usually highly specialized, and is focused on problem-solving skills in a narrowly defined subject area.

There are two types of knowledge in expert systems: public knowledge and heuristic knowledge (ref 6). Public knowledge includes documented definitions, facts, and theories. Heuristic knowledge is private, undocumented, based on individual experience. The knowledge captured in the NEWCS includes public knowledge shared among welding engineers, welders, and control engineers in textbooks, monographs, and journals. It also contains heuristic knowledge, including salient features of the journeyman welder's years of experience.

Knowledge is typically represented as one or more sets of rules. The advantage of rule-based representation is that knowledge is handled in a modular, easily understandable form. Rules consist of statements in the form of condition-action pairs, as shown in in Figure 1.

Rule 25

```
IF
        The torch is positioned in the center of the groove
  AND
        The groove is opening up
THEN
        Increase weave width
  AND
        Consider
                Increasing heat input & deposition rate
            OR
                Slowing down travel rate
```

Figure 1 - Rule-based knowledge representation

This rule states that if it should happen the torch is positioned in the center of the groove while at the same time the groove is opening up, the system should increase the weave width, and should consider two other possible actions: increasing the heat input and the deposition rate, or slowing down travel. A rule whose conditions are satisfied can "fire," causing its action to be executed.

At runtime, the expert system cycles through three operational phases in selecting and executing appropriate actions. As shown in Figure 2, these phases are called matching, conflict resolution, and action (ref 7). During matching, the system finds all applicable rules by testing their conditions. This phase generates a set of proposed actions, called the conflict set. During conflict resolution, the system resolves these conflicts. There are several strategies for resolving conflicts among rules, such as first come first serve, rule priority, rule specificity, and rule recency. The NEWCS uses a kind of rule priority strategy called goal reduction; priorities are defined using metarules to arbitrate among contending system goals. This strategy is presented more fully below, in the section on multiple goals.

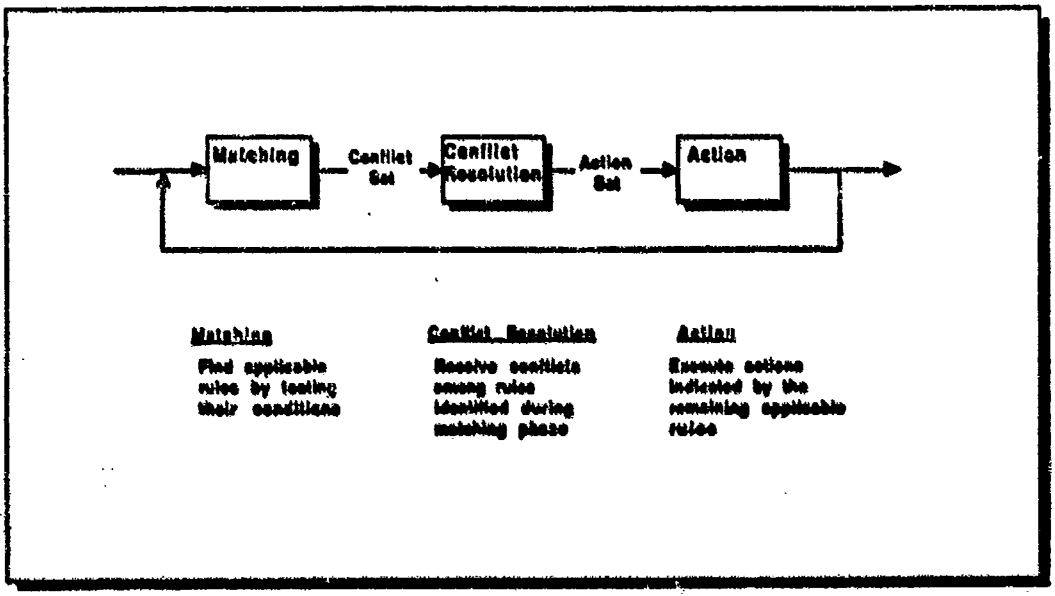

Figure 2 - Phases of the expert system execution cycle

Conflict resolution produces a subset of actions called the action set. This output becomes input to the action phase. During the action phase, the rules in the action set "fire," causing new output to the user, execution of selected procedures, or insertion of additional information into working memory, for use in the following cycle.

There are a number of risks associated with expert systems. For example, they cannot detect when a problem is beyond their scope, and do not degrade gracefully. They lack general problem solving skills people take for granted. Consequently, applications requiring a large body of general knowledge may be unsuitable for expert systems. Although the modularity of rules is advantageous during system development, strongly constrained interaction among rules can lead to inefficient performance, and in large rule bases, control flow can be difficult to follow. While situation-action knowledge is expressed naturally, algorithmic knowledge is not.

Risks such as these serve to limit the range of applications suitable for expert systems. Applications should be clearly scoped and must require only a modicum of common sense knowledge. They should have only modest real time requirements, and should be susceptible to heuristic, rule based expression rather than algorithmic implementation.

In addition to these risks, if the NEWCS is to be of practical value, it must satisfy some requirements unique to the shipyard environment. Foremost among these requirements, perhaps, is the need for co-worker systems. Co-worker systems are cooperative expert systems which share a knowledge base. Two types of joint information need to be exchangeable among co-worker NEWCS: long and short term experience. Exchange of long term experience must take place when a NEWCS unit is first installed in a shop. It must consult other units that have been in operation to bring itself up-to-date. Short term experience must be exchanged in handling extremely long welding jobs, such as in assembling segments of a submarine hull, where two NEWCS units are operating on the same joint 180 degrees apart. When one of these units gets to a location previously occupied by the other, it must consult the other unit for joint history.

The Naval Expert Welding Control System

For the most part, the use of expert systems in welding has been exclusively applied either before or after execution of the welding process (refs 4,8,9,10,11,12,13). Systems used before welding we call pre-weld expert systems. Examples include expert emulations of joint design, welding process selection, material selection, welding procedure determination, and pre-weld inspection. Systems used after welding we call post-weld expert systems. Examples of these include fault diagnosis and weld inspection interpretation.

We have adopted a different approach to applying expert systems to the welding field. We are exploring the use of expert systems as a means of providing intelligence for process control during the execution, or in-process, phase of welding, with particular emphasis on small batch arc-weld operations typical of the Naval shipyard environment.

While the focus of this in-process approach centers on weld execution, its impact is distributed over selected aspects of all stages of welding. Thus, during weld planning, the NEWCS reduces requirements for operator qualification, yet has little effect on process, position, or consumables planning. In weld execution, joint and equipment preparation remain much the same, while the welding operation itself and some aspects of quality assurance are automated. Finally, during post-weld processing, activities associated with inspection, diagnosis, and documentation are each subject to partial automation.

The relationship of the NEWCS to other components of the welding system is shown in Figure 3. The NEWCS is at the center, where it receives high level sensed information, evaluates it, and directs operation of a conventional welding control subsystem. The other components of the system are accessed as appropriate during weld set-up, weld execution, and post-weld analysis.

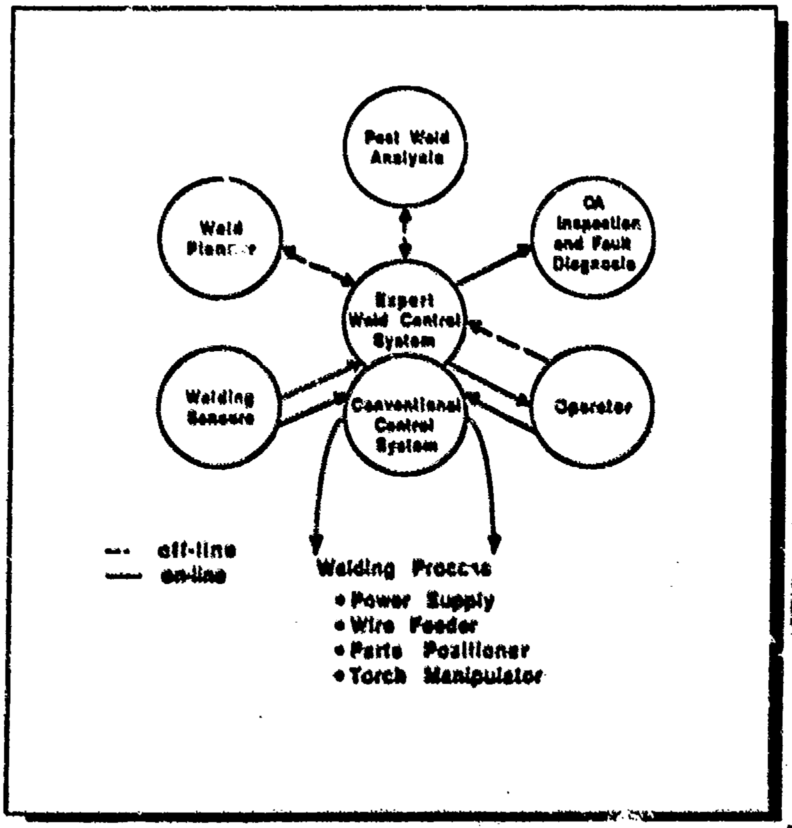

Figure 3 - Components of the expert welding control system

Prior to welding, the NEWCS receives data about the weld set-up from the weld planner through an off-line communication link. This includes information about part geometry, robot path (as determined by off-line

CAD), and weld parameters such as current, voltage, travel speed, gas type, wire type, torch orientation, number of passes and bead sequence.

During weld execution, the NEWCS receives information about the weld operation from several sources, including welding sensors, the welding control subsystem, and the operator. Based on its evaluation of this information, the NEWCS identifies conditions varying from the preset weld procedure, analyzes these conditions, and modifies the weld procedure accordingly, in much the same manner as does a human weld operator. It then advises the welding control subsystem as to how to handle these anomalies occurring during the weld. As part of its analysis of weld conditions, the system provides some in-process inspection and fault diagnosis.

Also during weld execution, information about the weld process and the system's decision-making is displayed on-line for the operator to monitor and evaluate. Although the NEWCS is highly autonomous and requires little operator intervention, it is important that its decisions be depicted in a highly visible and transparent manner. Because of its importance to the success of the system, the user interface is discussed in some detail below.

After welding, the NEWCS communicates data upstream to an engineering station. At this station data can be analyzed to identify and extract any errors in upstream operations, system performance, scheduling information and statistics about the weld operation, such as total arc-on time, cycle time, deposition rate per hour, and maintenance time.

Sensor Fusion

A combination of sensors is necessary to gather the information used in adaptive control of shipyard welding operations. Sensor fusion enables the system to arrive at a reliable interpretation of workpiece and equipment states, to anticipate future states, and to detect, diagnose, and correct faults. Sensor fusion improves system awareness and perception of the environment beyond the scope possible with evaluation of a single sensor, or separate evaluation of multiple sensors.

For example, sensor fusion plays a role in making intelligent fill rate decisions. For materials sensitive to heat input, fill rate decisions require combined support from both vision and temperature sensors. A vision sensor is used to capture the joint geometry and torch-to-workpiece location. A temperature sensor provides a temperature profile, including the cooling rate and thermal balance. The surface data from the vision sensor may be used to derive a fill rate, but this rate cannot be regarded as conclusive. Variations in workpiece thickness and clamping can cause unforeseen changes in heat sinking, and this can have an effect on the cooling rate. The temperature profile must be consulted to determine whether the cooling rate is within range to produce the mechanical properties required of the workpiece. If the cooling rate is not within range, the fill rate should be adjusted accordingly. Only by combining complementary information from two or more sensors can the system form the basis for intelligent decisions.

<u>Management of Multiple Goal Situations</u>

Management of multiple, concurrent, and often conflicting goals is another key element in the NEWCS. In performing a weld manually, the operator is continuously evaluating and coordinating the many indicators of quality: deposition rate, bead geometry, heat input, and others. This is accomplished based on the operator's experience, without reference to written rules or policy. Consequently, variabilities in human disposition have a great impact on the effectiveness of decisions. The complexity of these decisions, and the fact that the operator makes them in real time, in a dirty, noisy, smelly environment, means that they are usually sub-optimal.

Codifying management strategy for multiple goals would go far in making the welding process better understood. This in turn would make it more predictable and productive. By describing and ranking the various goals of the weld, one is forced to make quality, cost, and productivity tradeoffs in an atmosphere more conducive to good decision-making. Further, the analysis process leading up to strategy formulation would enable management to examine the consequences of particular strategies in advance.

Unfortunately, current practices dictate that decision-making be conducted "at the torch," as exemplified in an observation made by the weld engineering staff at the David Taylor Ship Research and Development Center. In submarine welding, yard management determines the productivity of the welder that produces the highest output while remaining within acceptable quality and cost. Policy for all others is then set at 80 percent of that level, the twenty percent providing a margin of safety for sub-optimal decision-making. The penalty for overall yard production is obvious. Thus an objective of the NEWCS is to allow managers to increase productivity to nearer the theoretical maximum.

For any given goal, there is a set of solutions that will satisfy the goal, called the <u>feasible set</u> of solutions. Solutions differ in terms of the degree to which they satisfy the goal. In choosing a solution from the feasibility set, decision-makers use the goal to eliminate the sub-optimal solutions. Eventually, one solution is selected that best satisfies the goal. This is referred to as the <u>optimal solution</u>.

If there is more than one goal, however, there is no guarantee that all goals are compatible. More than likely, they will conflict. This complicates considerably the process of reducing the feasible set to an optimal solution. Consider the example in Figure 4. Two goals are represented, output and cost:

(1) maximize the output of the welding process
(2) minimize the cost of the welding process

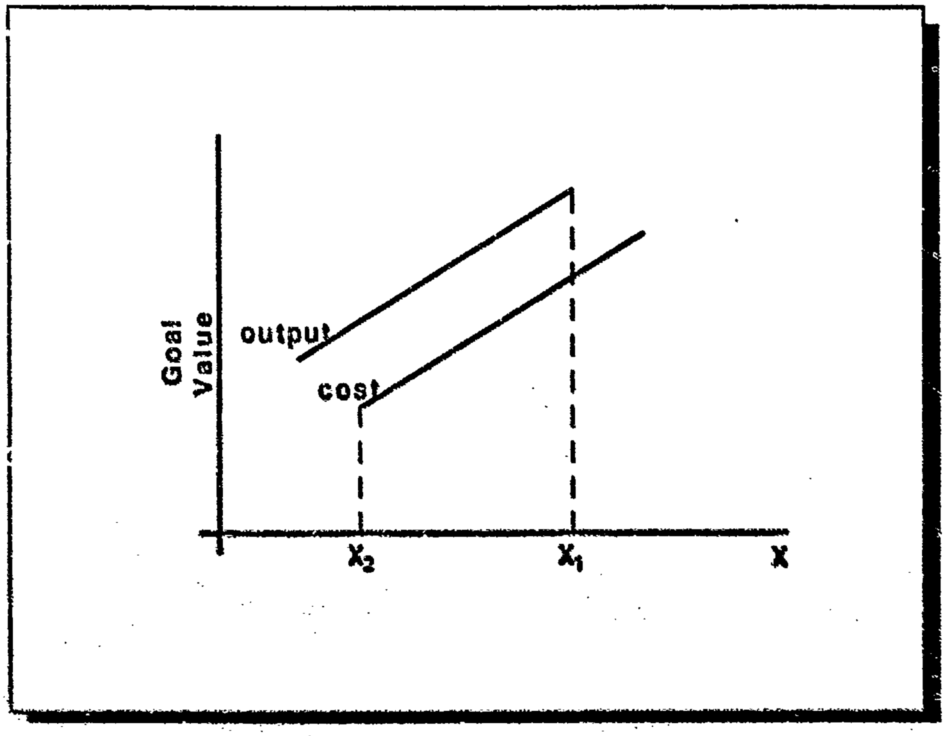

Figure 4 - Multiple goal optimization points

Considering each goal individually, the process should operate at point X1 to maximize output and X2 to minimize cost. However, the process can operate at only one level at a time; thus these two goals cannot be optimized independently.

As shown in Figure 5, if more than one goal exists, the point that will optimize each goal independently, the ideal solution, is not contained in the feasible set of solutions when the goals are considered together. In other words, the ideal solution is infeasible.

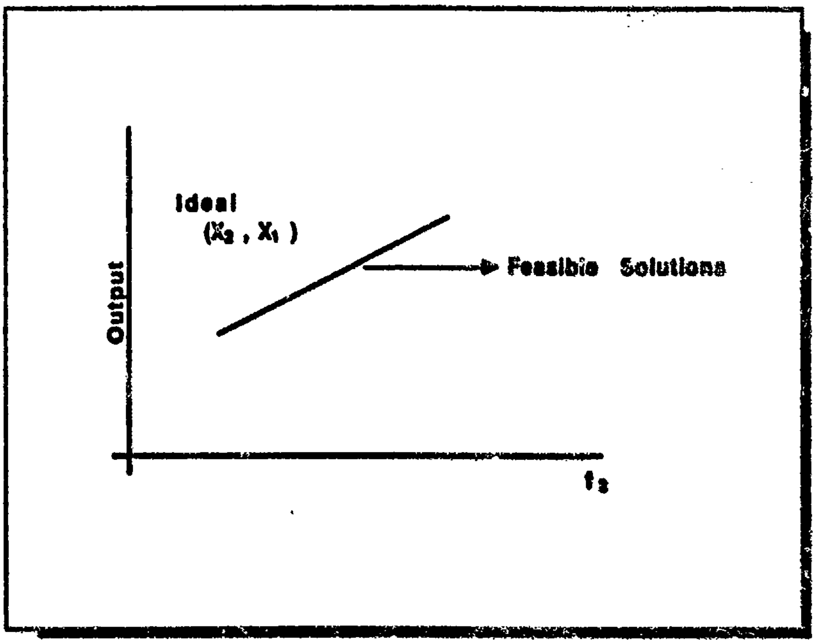

Figure 5 - Ideal solutions vs. the feasibility space

Conflicts among goals are common to the welding environment, and it is necessary that the NEWCS adopt a strategy for resolving these conflicts. There are two possible ways to do this.

First, multiple objective programming techniques can be applied. At present, however, this technique will not handle situations that have many variables or goals, and it is not practical in most real world situations. Further, if there are any changes in the circumstances surrounding a decision, the entire problem must be re-specified and run again. This is very time consuming at best.

Second, the multiple goal problem can be reduced to a single goal problem. This is the approach taken in the NEWCS. Goal reduction is accomplished by prioritizing the goals and designating the most important goal as the <u>optimized goal</u>. The remaining goals become <u>constraining goals</u>.

In order to optimize a goal within the bounds of other constraining goals, it is necessary to specify each goal quantitatively, as a desired level of attainment. This level is a threshold value that must not be violated. If a candidate solution to the optimized goal would violate the threshold value of a constraining goal, the value of the optimized goal must be changed. If changes required of the optimized goal would force it below its own threshold, the problem has been improperly specified.

The optimized goal is the goal most important at a particular time, and may change with time, due to shifts in external factors or in the availability of information. For example, at the start of a welding project, cost may be of prime importance, and this will drive the project. As time passes, however, it may become evident that the project must be completed sooner than expected, and the importance of cost may give way to throughput. Thus, the optimized goal is dynamic. This in turn will change the constraining goals, and their threshold values may change, also.

Figure 6 shows an example of multiple goal management expressed as a rule in a knowledge base. From this example, we can see that so long as the constraining goal, heat input, is well within its limits, we can maximize the optimized goal, deposition rate. However, when the constraining goal threatens to violate its threshold value, it becomes necessary to make a trade-off, and decrease travel speed.

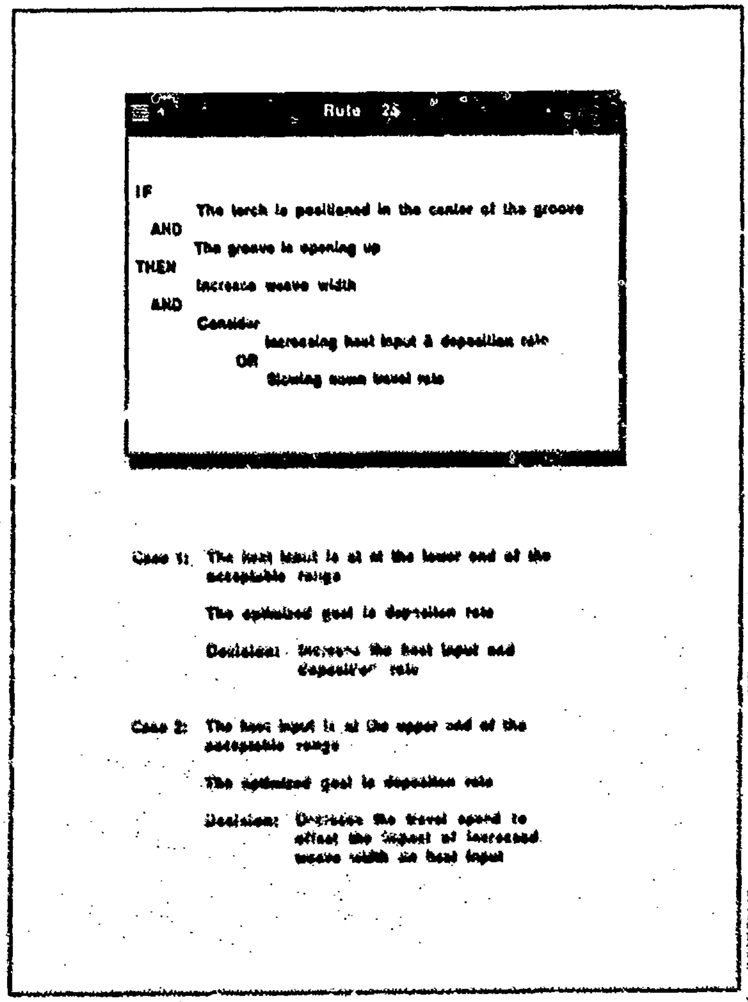

Figure 6 - Multiple goal management and rule-based knowledge representation

The Operator Interface

During weld execution, the NEWCS is highly autonomous, and needs little operator intervention. The functions of the operator consist primarily of monitoring weld progress, evaluating the system's decision-making activities, and replenishing consumables as needed. If the NEWCS is to inspire confidence sufficient for its acceptance at the work site, its interpretation of weld conditions and its response to these conditions must be portrayed clearly and transparently.

Several elements enter into making the NEWCS operator interface effective. If the interface is to be intuitive, information should be represented in terms familiar to the welding domain. The operator requires a rich set of commands for probing weld and system conditions, but demands for memorization should be minimized. The interface should give the operator the power and flexibility to bring together various arrangements of information on an ad hoc basis, with a full range of perspectives, in accordance with the needs of the moment. Lastly, the mechanism for interacting with the system should be instinctive and simple.

Our approach to the NEWCS operator interface is based on direct manipulation, using displays like the one shown in Figure 7. Interaction is organized around the use of a pointing device, such as a touch screen or track ball. Information is presented symbolically, using graphics to depict weld conditions in a way familiar to operators. Operator commands are supported by advanced menu techniques, including pulldown menus, dialogue boxes, and other choice structures. Windows let the operator rapidly adapt status readouts according to passing circumstances. The pointing device lets the operator easily navigate among interactive symbols, menus, and windows populating the display when tracking NEWCS performance.

The ability of the NEWCS to explain its decisions is important to system credibility. Explanations provide the operator with a view of the current strategy, the factors governing the strategy, and the options concomitant to the strategy. Explanations cannot afford to rely solely on text; pictorial and metaphorical representations are more easily grasped, especially when implemented as interactive entities capable of sustaining operator exploration and manipulation. From the operator's perspective, explanations are integral to the system, not the product of a subsystem developed as an afterthought.

Off-line, the NEWCS interface provides operators, designers, and weld engineers with capabilities useful in maintaining the NEWCS. The approach is similar to the on-line operator interface, except it also has facilities for tracing, replaying, and simulating selected weld segments, and for editing the NEWCS rule base.

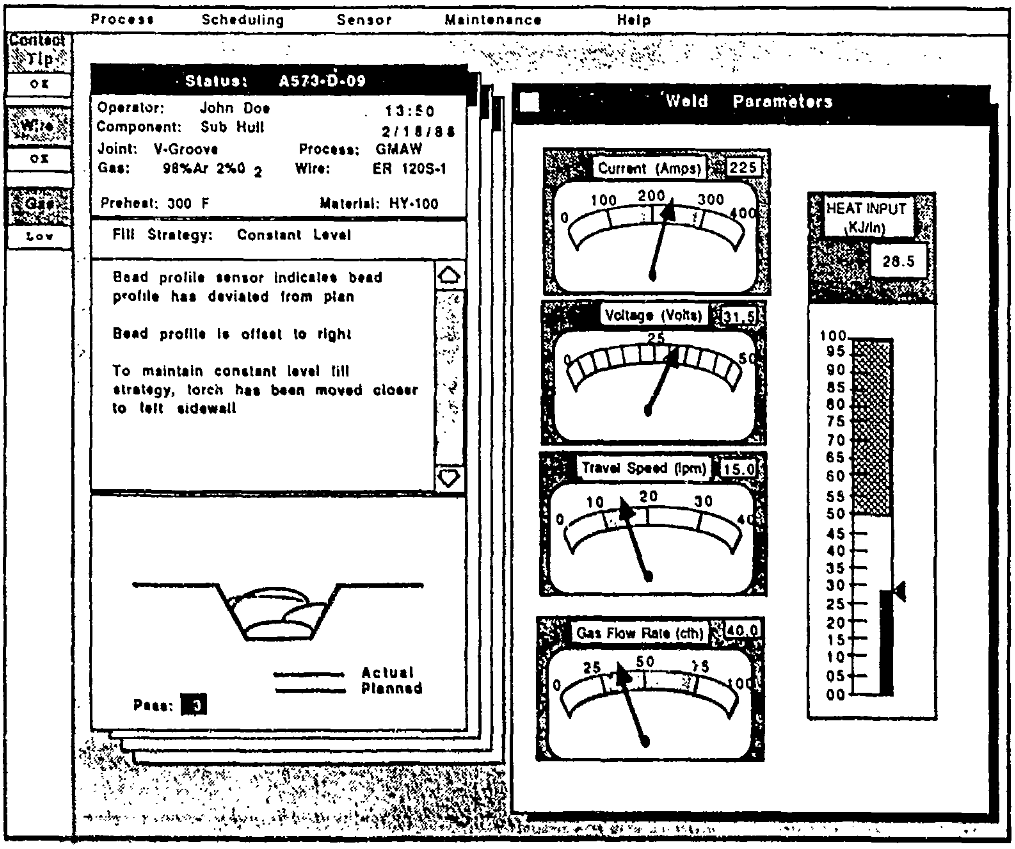

Figure 7 - Operator interface display

The NEWCS Model

For the NEWCS to be of practical value, a generic approach needs to be taken in its design; a spectrum of capabilities is required to apply it to a variety of weld problems. This is accomplished by two means: 1) phasing system development into a set of steps that minimize the redundancy of effort required each time the NEWCS is applied to a new weld, weld application, or weld process, and 2) partitioning the system into a set of components amenable to tailoring the NEWCS for the broadest possible application.

Development Phases. As shown in Figure 8, the steps involved in applying the NEWCS include engineering of aspects generic to all weld processes, engineering of versions particular to the selected weld process, customizing data specific to the particular weld joint application, and monitoring and evaluating the NEWCS during weld execution.

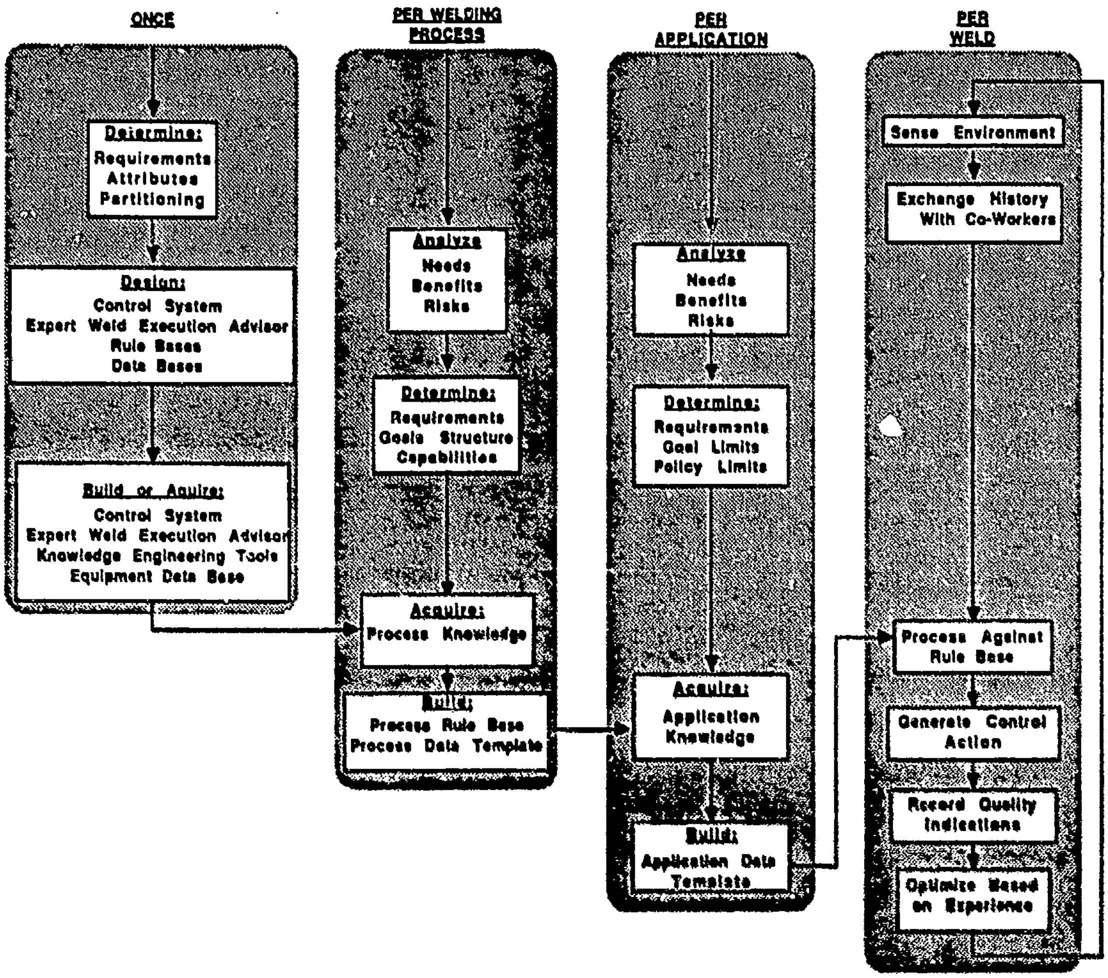

Figure 8 - Steps in applying the NEWCS to multiple weld processes

The initial generic engineering lays the groundwork for application of the NEWCS to specific weld processes, such as SAW, GMAW, or GTAW. This includes determining the requirements and refining the partitioning for the system, developing the generic control and advisory systems, and selecting knowledge engineering tools appropriate to subsequent development work.

Weld process engineering consists of process analysis, requirements definition, knowledge acquisition, and data base development. Ideally this should be required only once per process, although there are variables that may dictate several variations for situations like GTA and hot wire GTA welding, plasma arc and variable polarity plasma arc welding, and GMA and plasma GMA welding.

The principal outputs of process engineering are a rule base and set of data templates for a specific weld process. The rule base contains the knowledge acquired from the experts in the particular process, including rules for the physics of the process, applicable joint configuration(s), equipment operation and process fixturing, and the framework for policy limits set by management. The data template is used later, during application engineering, to fill in specific data about the joint to be welded . These data condition the process rule base to such things as material thickness, weld position, edge bevel, number of passes, bead width, and policy limits. An example of part of such a template is given in Figure 9.

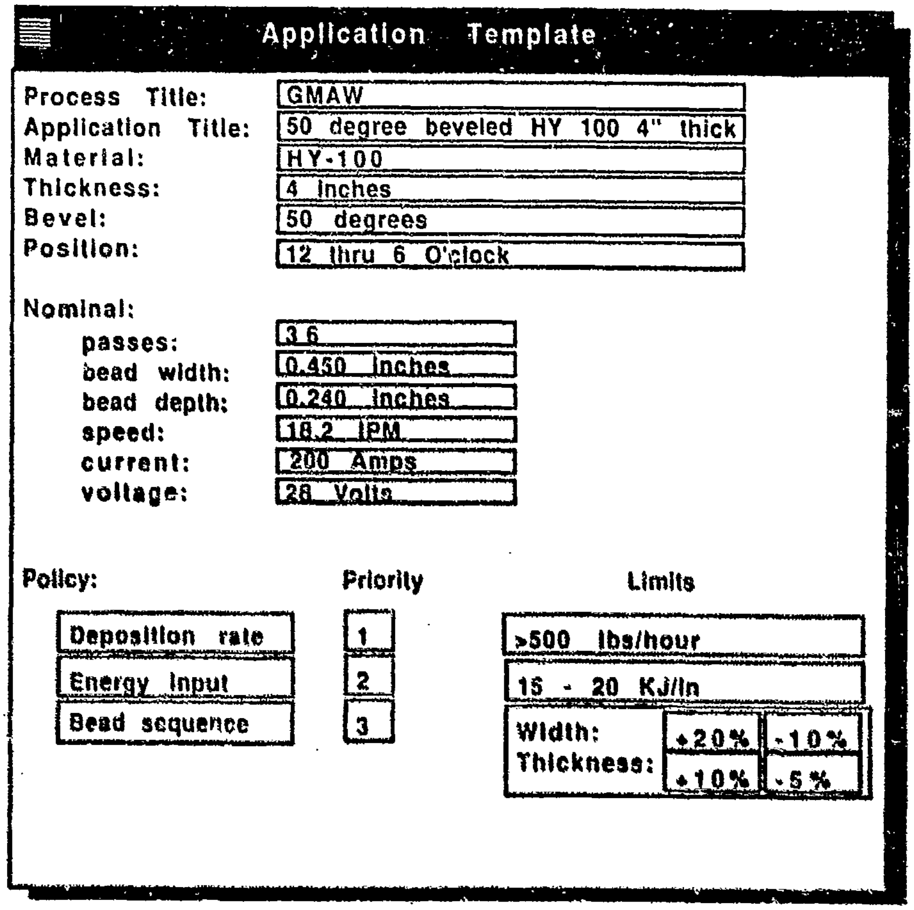

Figure 9 - Sample data template for GMAW process

Following weld process engineering, the shipyard weld engineer creates specific NEWCS applications. This is accomplished employing some of the same knowledge engineering tools used in the process engineering stage, but used in a more restricted way. The principal vehicle for the application engineering will be the data template. If process engineering has been thorough, application engineering should consist of little more than filling in the template with data describing the particular joint as to configuration, desired bead geometry, number of passes, acceptable heat input limits, multiple goal priority structure, required coordinations with co-worker NEWCS, history and quality data to be recorded, etc.

The dividing line between a weld process and weld application is not always distinct. Although GMAW and GTAW are different processes, within the GMAW process itself it is unclear at what point of variation in tooling, equipment, material, or joint configuration it is necessary or wise to describe a new process with an associated rule base and template. This dividing line will probably be dictated by the degree to which the process rule bases can be made general in nature and broad in applicability. The dividing line thus becomes a function of how much complexity in a given rule base and how much speed degradation in the inference engine we are willing to accept in order to preserve generality.

Once completed, application templates go in the NEWCS application library and are available to the weld operator for use in weld execution. During weld execution, the NEWCS accesses rule and data bases to generate control actions, record quality indications, and self-optimize its performance based on environmental factors and data received from concurrently operating co-worker systems. The NEWCS provides the weld operator, quality assurance staff, and co-worker NEWCS with sufficient data during a particular weld that they can monitor progress. In addition, the NEWCS provides the weld engineer, management, and the NEWCS system engineer with data pertaining to long term performance of the system.

System Partitioning. As shown in Figure 10, system components consist of the process engineering laboratory, the application engineering laboratory, and the field location set-up. This partitioning is designed to support iterative development of successive weld processes and applications. It provides a functional, maintainable architecture for the NEWCS.

The process and application engineering laboratories provide knowledge engineering tools used to collect and organize process and application knowledge from various experts. In the field location set-up, an expert weld execution advisor and matching control subsystem supervise welding equipment using the rule bases assembled by the knowledge engineer and the weld procedure templates assembled by the weld engineer.

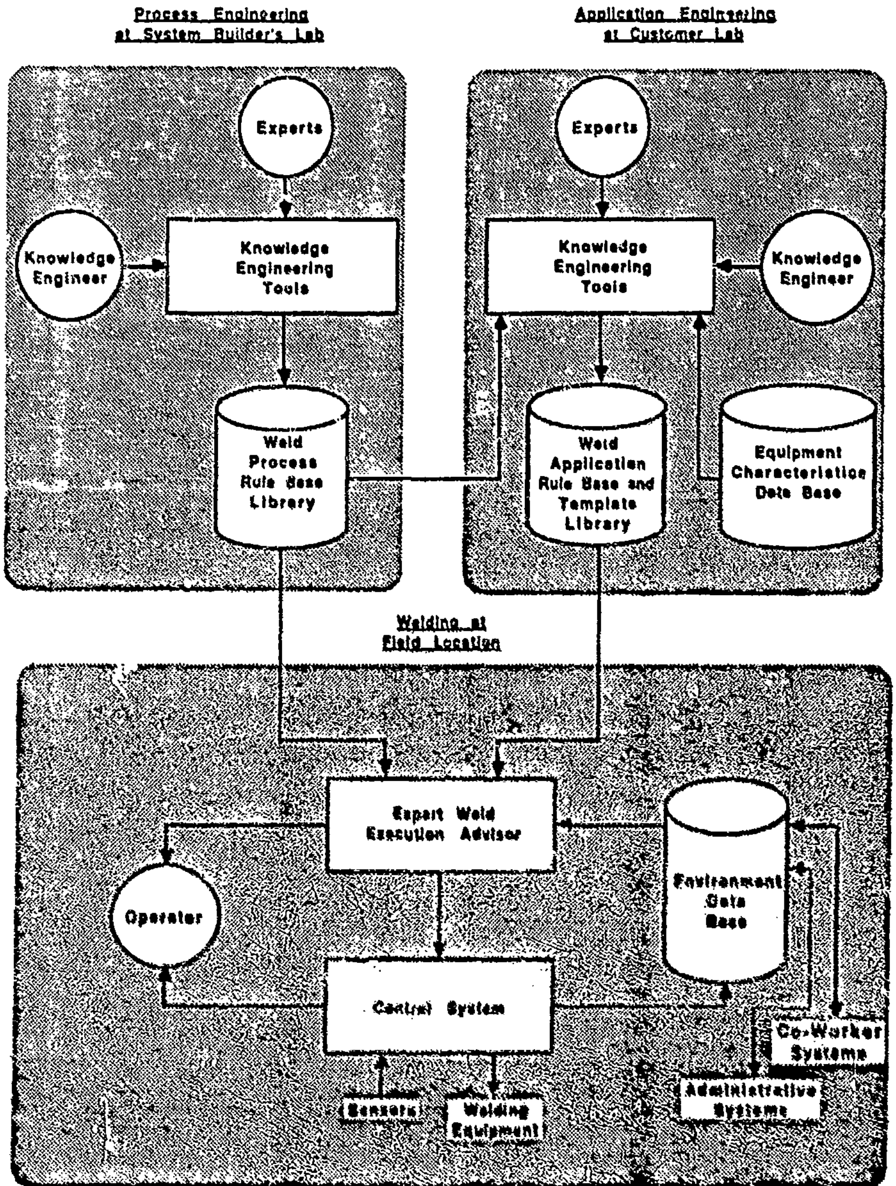

Figure 10 - NEWCS system partitioning

Conclusion

Artificial intelligence technology has much to offer the shipyard welding situation. In particular, the use of expert systems, the best developed branch of artificial intelligence technology, offers a set of behavioral characteristics for a welding control system that can significantly improve the productivity, quality and reliability of shipyard welding activities.

The simultaneous management of several goals is one of the major challenges in such a system. The goals of maximized productivity, maximized quality, minimized cost, and management policy can often conflict when variations occur in the parts to be welded. During the weld these goals must be traded off in light of the facts of the particular circumstance, and decisions must be made regarding changes in welding parameters within a matter of a few seconds.

Human welders do this by relying on their accumulated experience base. Our studies show that as competent welders become more and more scarce, expert system technology can be used to extract their knowledge in a form suitable for control system purposes. An expert welding control system would conduct the weld in the same fashion as the human operator, but with enhanced reliability and performance. It would allow management to increase productivity to nearer the theoretical maximum without jeopardizing quality, and provide improved visibility into system performance, thus increasing confidence in the overall operation. By structuring the NEWCS generically, it can be applied to many different shipyard welding situations without significant change in the system itself.

Acknowledgement

This work was sponsored by the Naval Sea Systems Command, Department of the Navy, under contract #N00024-87-C-5121.

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Advantages of Off-Line Programming and Simulation for Industrial Applications

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Session VII Program A

Manufacturing of Aerospace and Military Systems III

Chair: J. W. Anderson, USAMICOM

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Presented at the Conference on Space and Military Applications of Automation and Robotics

21-22 June 1988 GACIAC PR 88-02

A 3-D GRAPHICAL SIMULATION OF AN AUTOMATED DIRECT CHIP PROBE/TEST SYSTEM

June 1988

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ABSTRACT

This paper describes the development of a 3-D graphical simulation of a Direct Chip Probe Test System (DCP/T). The DCP/T system is an automated probing system that performs full dynamic electrical testing under thermal stress on integrated circuit die (chips). These tests are necessary to insure that the die passes military specifications. The simulation was developed using MCAUTO robotic simulation software and an Evans and Sutherland graphic workstation. The simulation was used to verify DCP/T mechanical and dynamic operating parameters and to assist in the design of a second generation die testing system. By dividing the probing system into subsections or modules, we were able to treat them as "mini-robots" and simulate all equipment movement and probing process steps using the robotic simulation software.

INTRODUCTION

This paper describes a methodology, which was developed jointly by MICOM and UAH, for using commercially available Robotic Simulation Software (RSS) to design and simulate advanced manufacturing equipment.

RSS is used in conventional applications to simulate robotic devices, and allows manufacturing engineers to develop automated workcells from existing robotic libraries, or utilize CAD (Computer-Aided Design) software tools to create robotic devices.

The RSS software in use at the MICOM Advanced Manufacturing Research (AMR) facility is MCAUTO, which was purchased from McDonnell Douglas. The system provides applications for defining movement and motion for robotic devices which are relational to real-time performance. Complete multi-axis devices can be defined and integrated with graphic models to display manufacturing workcells (see Figure 1). Then software sequences may be developed to program the devices to perform simulated manufacturing tasks. CNC code is available for off-line programming robots.

Our requirements were different from conventional RSS applications in that the need was to simulate detailed graphic models of advanced and automated manufacturing equipment. Manufacturing Design and Simulation (MD&S) software tools were needed to provide the capability to design

advanced manufacturing systems and simulate real-time graphic models. An MD&S approach could provide a low cost method to support research and development for missile manufacturing concerns.

A microcircuit test system, the Direct Chip Probe/Test (DCP/T) system (see Figure 3), was used as the prototype MD&S model for this project. CAD software was used to create a detailed 3-D graphics wire-frame model of the DCP/T system (see Figure 4). The system was subdivided into isolated modules and represented as one or two-degree of freedom, robotic devices.

From this point, engineering concentrated on using robotic device definition software tools to create motion and movement for working components of the DCP/T.

THE DCP/T SYSTEM:

Work was initiated in microcircuit chip (die) probing technology by the U.S. Army Missile Command as a result of low yields and high production costs involved in the production of complex Hybrid Microelectronic Assemblies. Low yields and high production costs have provided the driver to develop technology for pre-screening die under thermal stress prior to assembly into HMA packages. Subsequently, the Army has developed a direct chip probe/test system (DCP/T) to perform dynamic testing at hot and cold temperature extremes (see Fig 4). The automated DCP/T is capable of picking die from standard waffle packs, probing and performing electrical tests on each die at selected temperatures, and sorting the tested die depending on the electrical test results.

Of major importance is the unique capability of the DCP/T to perform full dynamic testing on individual die at ambient temperature, and at specified hot and cold temperature extremes with a single probe of each die.

The complexities of precision mechanical placement and positioning of the microcircuit die are such that enhancements were needed to improve the DCP/T. A new alignment module could utilize pattern recognition and micro-positioners for die alignment, and eliminate possible damage to the die due to mechanical handling techniques used on the original DCP/T design.

The DCP/T system uses a dual position, pick-and-place arm (see Figure 5) wich provides input and output of die from a waffle pack and transfer to the probe/thermal test chamber. The picking of each successive die therefore requires the input table to be indexed to properly position each die at the pick point in a sequential manner. Likewise, the output table is indexed to accomplish the desired sorting of the tested die. After a new die is picked from the input table and placed on a rotary table, a mechanical centering mechanism (see Figure 6) closes on the die to provide final alignment and precise positioning. A vacuum is then applied to a small orifice under the die to secure its position on the table. The Anorad rotary table then rotates and presents the die to the temperature chamber for thermal screening during concurrent electrical test.

The Anorad table allows manipulation of two die. The table and dual arm positioner was designed such that die are picked and place to in-put / output stations while a second die is undergoing thermal screening.

A concept was developed under previous Advanced Manufacturing Research tasks to replace the DCP/T mechanical alignment module with a pattern recognition, intelligent positioning module.

If successful, the results of this project would provide a low cost software tool to make design enhancements to the DCP/T and evaluate concepts with MD&S methods, versus traditional methods of making costly hardware changes to prove out design concepts.

MD&S APPLICATIONS DEVELOPMENT:

Three-dimensional graphical models of the DCP/T system were constructed using Computer-Aided Design (CAD) software. Wire frame models were created based upon measurements of the actual equipment.

The MCAUTO software allows wire-frame simulation and animation of robots with up to six degrees of freedom (DOF). For each robot, a BUILD file is developed that describes the physical characteristics of that robot. These include joint type (translational or rotational), limits, velocities, and the type of motion. By defining these real-time operational characteristics, an accurate robotic graphical simulation can be developed. For this project, we did not have any robot to describe. Instead, we had an highly-complex, automated piece of machinery that has five precision moving subsystems. The subsystems are:

(1) Dual-Position Transfer Arm

(2) Anorad Rotary Table

(3) Input Station

(4) Output Station

(5) Alignment Mechanism

The graphical model of each of these subsystems is shown in figures 3 through 7 respectively. Each subsystem was "broken" into two elements. The fixed or non-moving element is designated as the base, while the other element is designated as the first link of the robot. The base and link are connected together in the MD&S software. At that connection is where the rotation and/or translation occurs for that subsystem. Each module was defined as a robotic device and the actual movement and motion sequences were developed. The methodology for user definition of models was documented, and thus the MD&S application was developed.

All DCP/T system hardware modules were developed using MD&S software tools. The modules devices were linked together to form the complete DCP/T system with real-time simulation execution.

The MD&S methodology provided a unique capability to recognize user defined models (advanced manufacturing systems) as robotic devices, and the DCP/T model was successfully developed.

RESULTS:

The MD&S application provided a valuable engineering tool to evaluate new concepts for die alignment. The model was modified several times and new DCP/T features were added to the 3-D simulation. A pattern recognition concept was developed to utilize a micropositioner to replace the mechanical alignment module. This proved to be an optimum approach to die alignment and eliminated possible damage to the die.

The MD&S application was then utilized to develop a manual version of microcircuit test system. A complete model was developed and used extensively to tweek and tune process steps. Advanced Manufacturing Research efforts are currently ongoing to develop a prototype MANTEST, manual probe/test system which will utilize a FTS thermal unit to provide thermal screening in the ranges of -55 to +125 degrees Celsius. Other applications are ongoing utilizing the MD&S methodology for advanced manufacturing systems design.

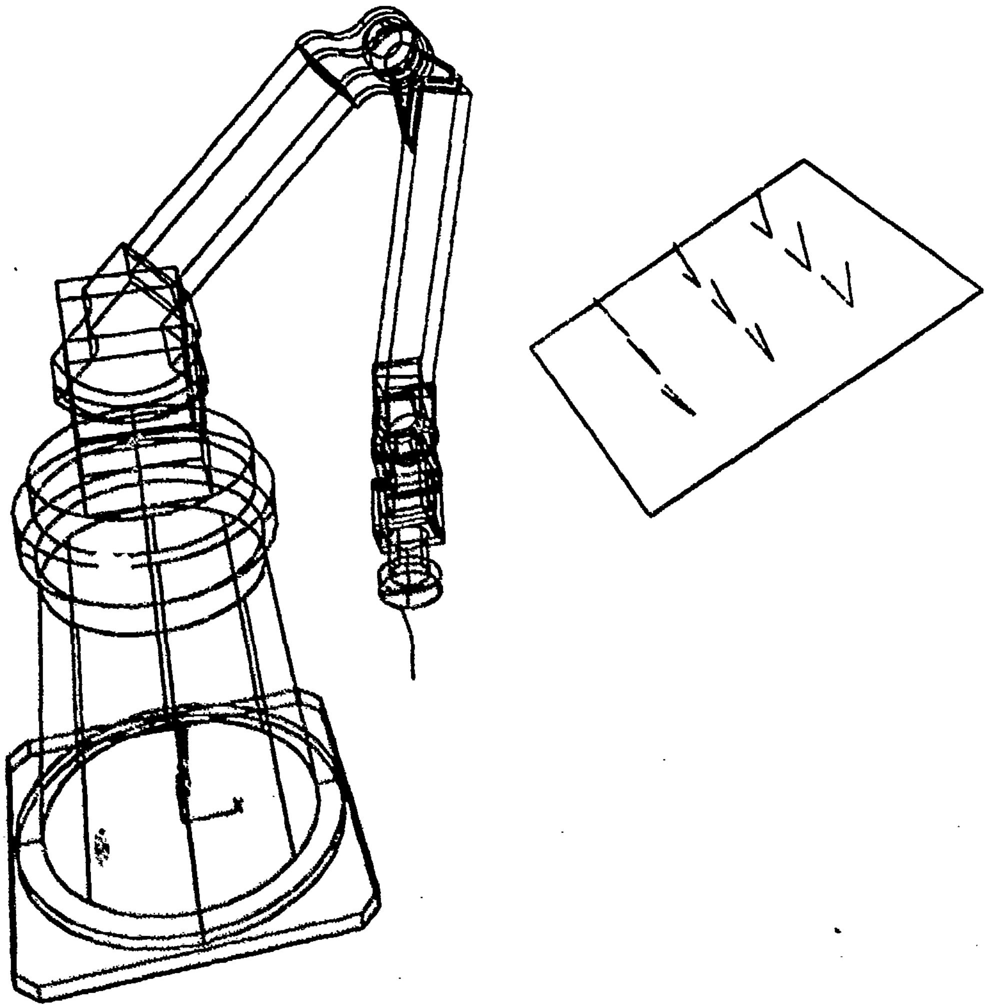

Figure 1. A GRAPHICAL MODEL OF A MANUFACTURING WORK CELL

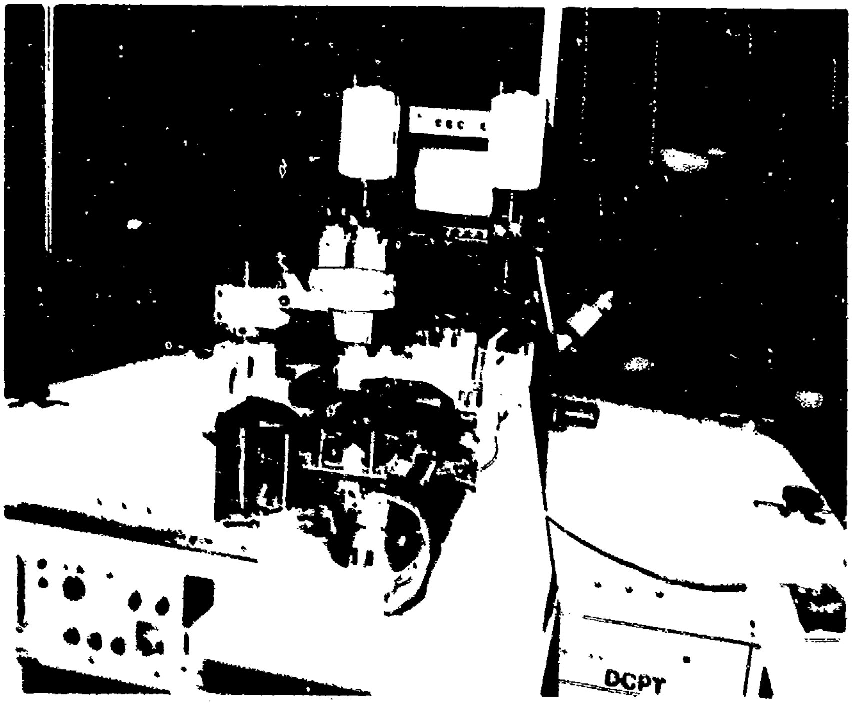

Figure 2. THE DCP/T SYSTEM

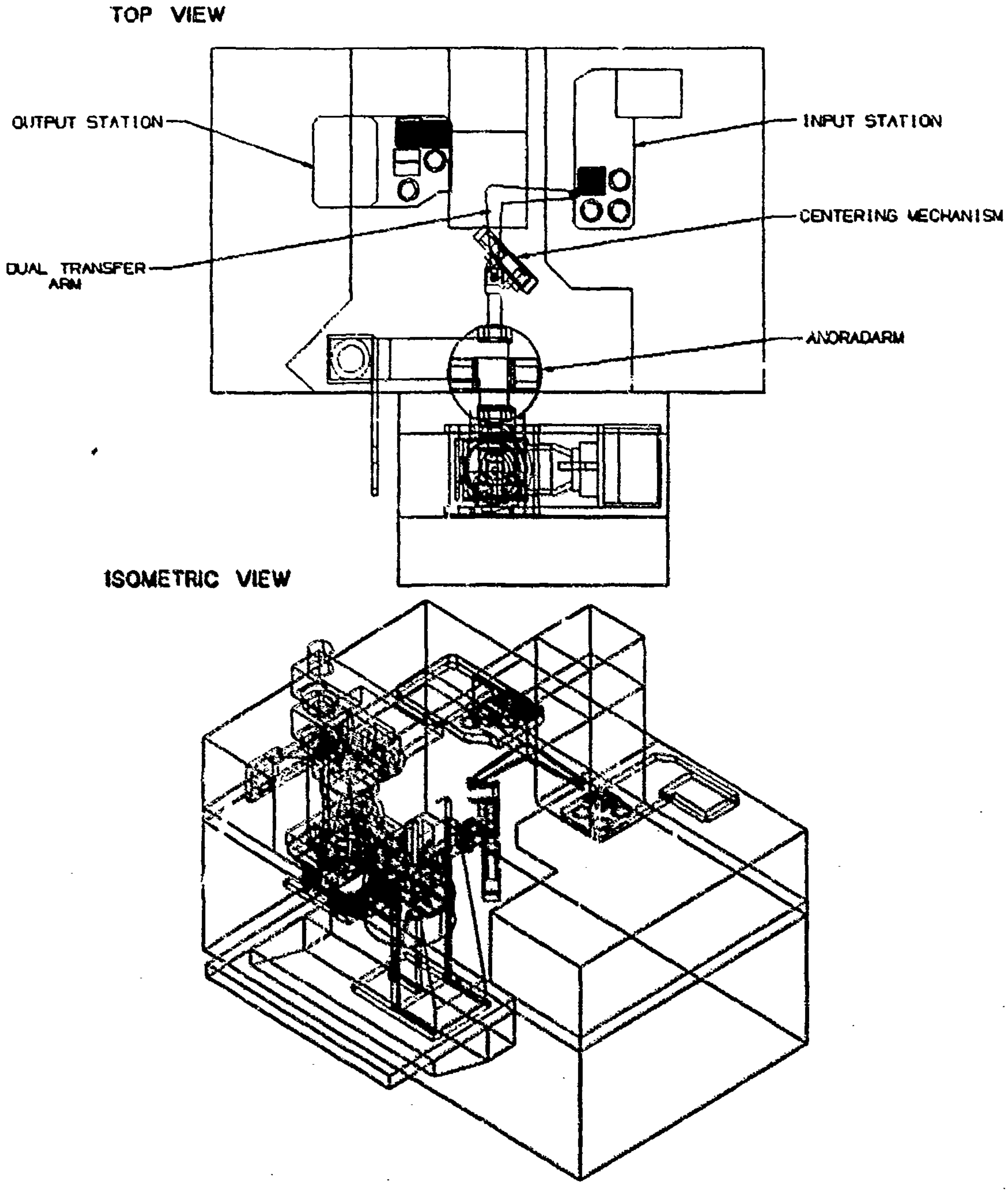

Figure 3. A GRAPHICAL MODEL OF THE DCP/T SYSTEM

Figure 4. CLOSE UP OF DCP/T

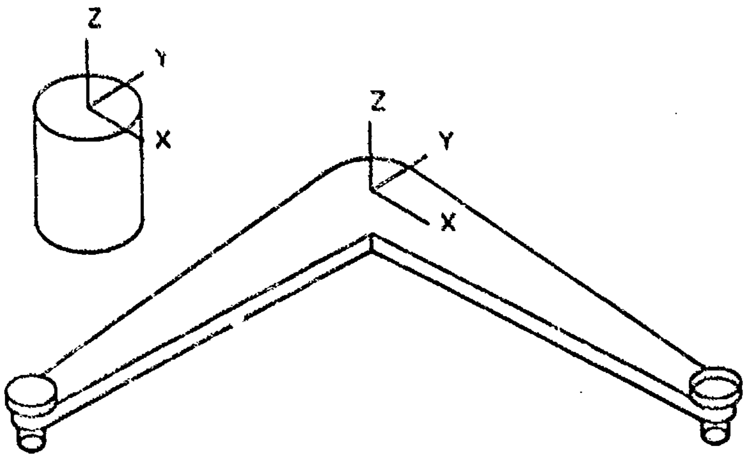

Figure 5. GRAPHICAL MODEL OF THE DUAL-TRANSFER ARM

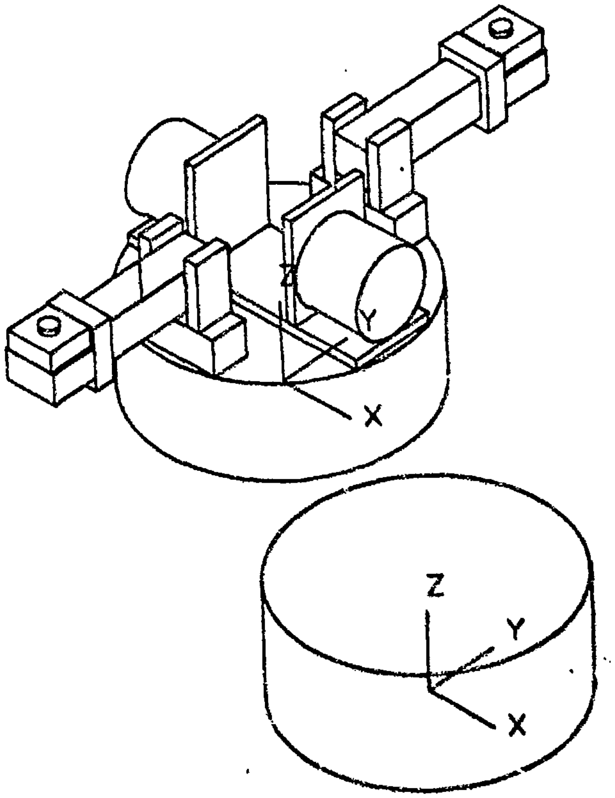

Figure 6. GRAPHICAL MODEL OF THE ANORAD ROTARY TABLE

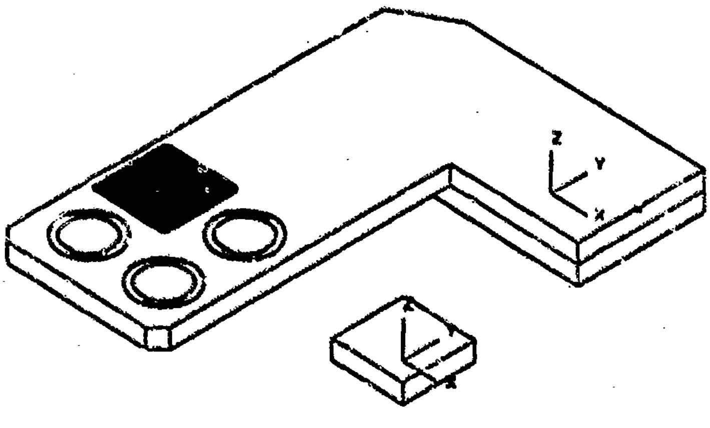

Figure 7. GRAPHICAL MODEL OF THE INPUT STATION

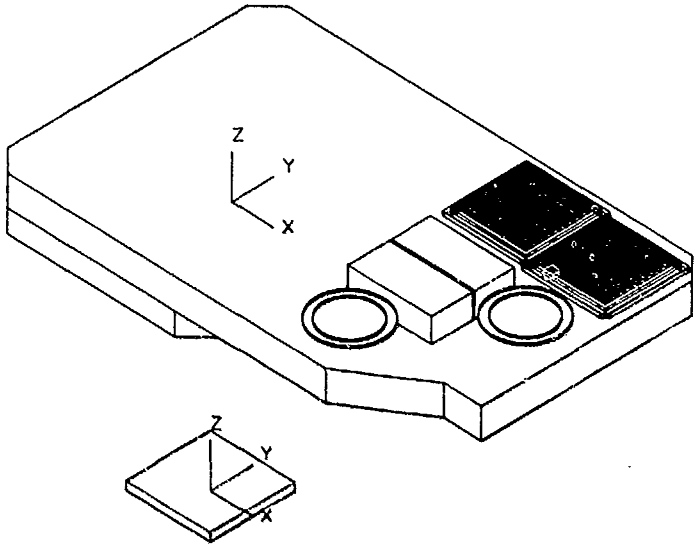

Figure 8. GRAPHICAL MODEL OF THE OUTPUT STATION

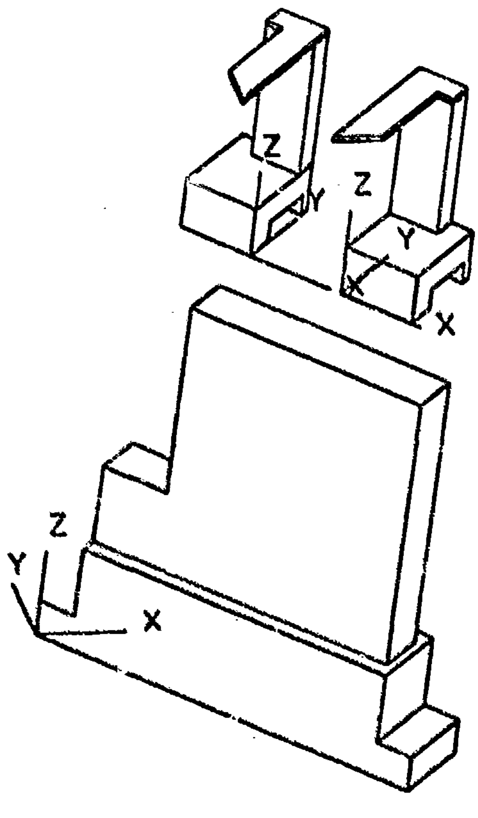

Figure 9. GRAPHICAL MODEL OF THE CENTERING MECHANISM

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AUTOMATED MANUFACTURING PROGRAMMING SYSTEM

30 March 1988

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ABSTRACT

This paper presents an automatic programming system of manufacturing simulation models written in GPSS/PC. Included in this paper are a description of the Automatic Manufacturing Programming System (AMPS) and the operation of the system.

1.0 INTRODUCTION

Ever since the early computers, there has been interest in having computer programs that help programmers write computer programs. The term commonly used to describe this approach is automatic programming (AP). Automatic programming is defined as an application of artificial intelligence (AI) that is concerned with automating some aspects of the computer programming process (Barr and Feigenbaum 1982). More specifically, automatic programming requires another program, an automatic programming system, to raise the level of specifying the program instructions.

One potential application area for AP is in discrete event simulation. There are several factors that make simulation a prime application area. First, to become a trained simulationist requires a considerable amount of training in and knowledge of the simulation language. Second, individuals that have the skills to develop valid simulation models are in short supply (Shannon et al. 1985) and in many instances are not even available.

A third factor that makes simulation a prime candidate for automatic programming is that the development of simulation models is time consuming. In fact, considerably more time is generally required to construct the model than originally estimated and more importantly, than available. A related factor is the requirement for employees who are familiar with the manufacturing system to assure model credibility and validity.

A number of approaches has been developed in using AP for simulation. One approach, and the most difficult, is to let the user specify his problem in a free text format and then have a program that will parse the text and automatically generate the simulation code. One of the earliest approaches was the development of an interactive natural language interface (NLI) (Heidron 1974). Through a series of questions, the system would automatically write the corresponding GPSS simulation program. More recently, another NLI approach (Ford and Schroer 1987) was developed that is domain specific for the electronics assembly industry. In this approach the target language wa SIMAN (Pedgen 1985).

A second approach, which is less difficult than the NLI, is to construct an interactive user interface. This interface consist of a set of icons that are mouse selected and connected together to form the system. Once the system has been constructed, the user then inputs the corresponding attributes. Another user interface, besides the graphic icons, is to use an interactive dialogue where the user responds to a series of questions. Then, based on the responses, the system automatically writes the simulation code.

Haddock and Davis (1985) have developed a system for modeling manufacturing cells. Through a menu format, the user defines the number and types of machines in a cell, part types, sequences of operation, buffer capacities, and various processing times. The system is written in Basic on a PC and automatically writes the SIMAN simulation code. Another example is a ruled based expert system that assists the modeler construct simulation models (Khoshnevis and Chen 1986). A set of ten icons, including transfer, create, service, gate, seize and alter, has been developed to assist the user graphically construct the model. The system automatically generates the corresponding SLAM simulation code. Brazier and Shannon (1987) have developed an automatic programming system for modeling AGVs. An interactive dialogue is used to define the AGV system. The system automatically writes the corresponding SIMAN simulation code.

2.0 AUTOMATIC MANUFACTURING PROGRAMMING SYSTEM (AMPS)

The AMPS system is a simulation tool to assist the modeler of manufacturing systems define his problem through an interactive user dialogue and to then automatically generate the corresponding GPSS/PC (1986) simulation code.

The approach in developing the AMPS system consists of the following phases:

- Select the manufacturing domain.
- Define the common manufacturing function for the selected domain.
- Write the GPSS macros of the manufacturing functions.
- Write the user interface program.
- Write the GPSS automatic code generator program.

2.1 Manufacturing Domain

T : AMPS system domain is those manufacturing systems that can be described as having:

- Assembly and subassembly lines where parts are being added to an assembly.
- Manufacturing cells that are providing parts to the assembly and subassembly lines.
- Inventory of parts being moved between the manufacturing cells and subassembly lines.

Figure 1 is an example of a typical manufacturing system consisting of one assembly line, two subassembly lines and two manufacturing cells. The assembly line consists of two assembly stations, one task station and one inspection station. One subassembly consists of one assembly station and one task station while the second subassembly line consists of two assembly stations. Manufacturing cell MC1 provides part type C for assembly station ASSY1 and part type H for assembly station ASSY8. Manufacturing cell MC2 provides part type E for assembly station ASSY5 and part types F and G for assembly station ASSY7. There are a variety of stock points, labeled A through L, located throughout the manufacturing system.

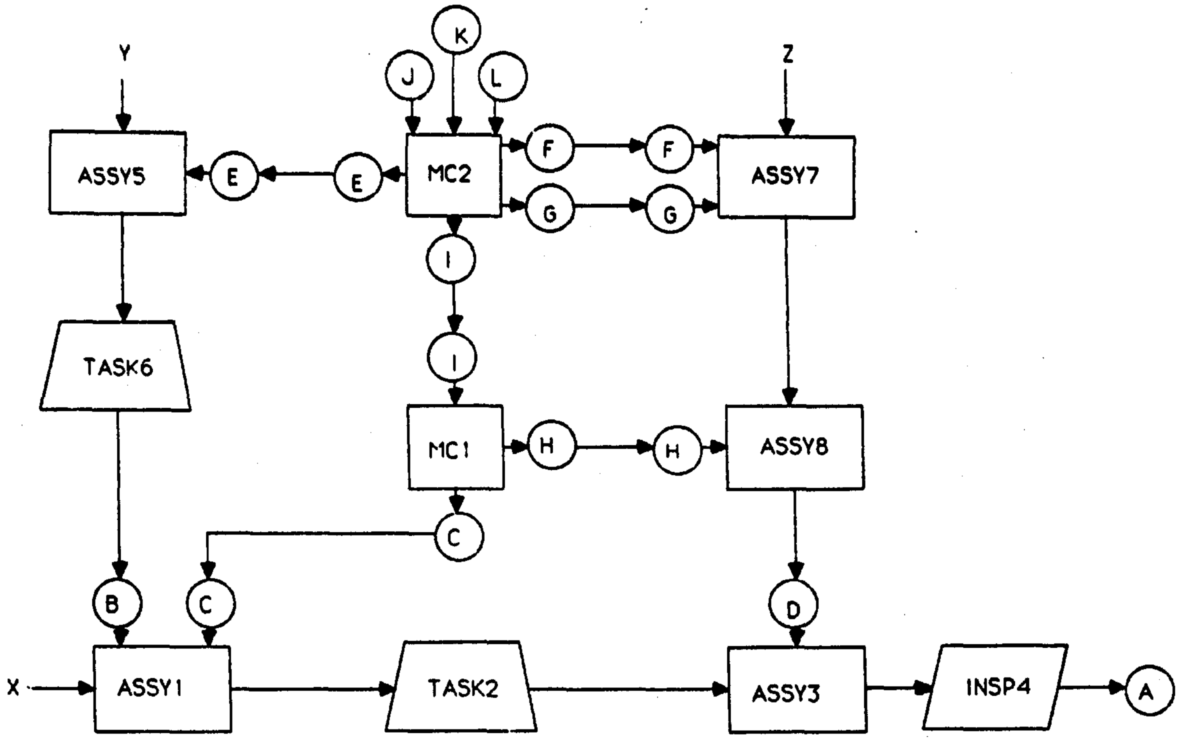

Figure 1. Manufacturing system

2.2 Common Manufacturing Functions

In analyzing most manufacturing systems at the macro level, the following functions are generally similar in nature:

- Assembly - adding part X to part Y resulting in part Z
- Fabrication - making of part X from part Y
- Inspection - inspecting part X
- Inventory transfer - moving part X or a cart of part X from stock point A to stock point B
- Simple operation - performing an operation on part X resulting in a modified part X

These five functions represent the current domain of manufacturing functions within the AMPS system.

2.3 GPSS Macros

Once the manufacturing functions have been defined, the GPSS subroutines can be written for each function. These routines constitute a library of predefined GPSS subroutines or macros. This library of macros are then called, when needed, in the construction of the GPSS simulation model. Currently, the AMPS system has the following five GPSS subroutines:

- assembly station
- manufacturing cell
- inventory transfer
- inspection station
- simple operation station.

Figure 2 briefly describes each of these macros. For example, the assembly station macro has the capability of simulating the adding of a variety of different items to the incoming part resulting in a modified part that is then transferred to the next destination, a station or stock point. For example, in Figure 2, station STA1 assembles 2 part C's and 3 part D's to the incoming part A resulting in part B.

The manufacturing cell makes a cart of specified parts when an order is received. The cell can make multiple part types. For example, cell MC1 makes one part A from two part C's and 3 part D's and one part B from one part D.

The task station performs an operation on a part. For example, in Figure 2 an operation is performed at station STA4 on part E resulting in a modified part E. The inspection station inspects a defined percentage of parts. Of those inspected, a defined percentage is defective. Of those defective, a defined percentage is scrapped.

The inventory transfer macro grants part requests from an assembly station or a manufacturing cell and checks if the inventory system is a push or pull. For a pull system the macro orders a cart of parts by sending an empty cart back to the source and sends a full cart of parts to the demand stock point from the source stock point.

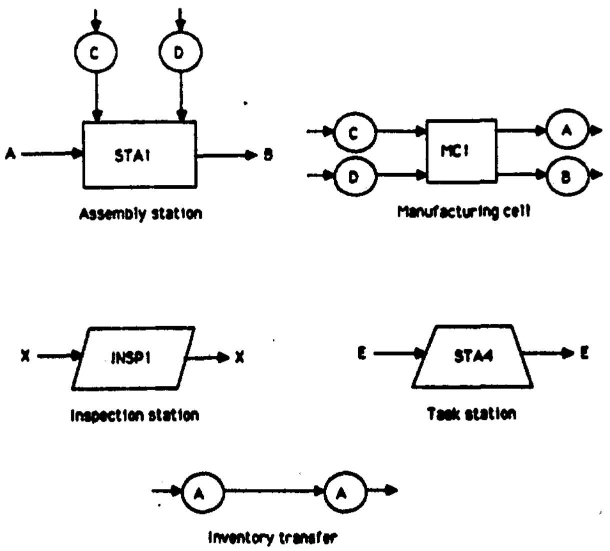

Figure 2. GPSS manufacturing macros

2.4 User Interface

The user interface is written in LISP on a Symbolics 3620 AI machine and consists of 530 lines of code and 51 rules. Figure 3 is a partial listing of the user interface dialogue for the manufacturing system in Figure 1. Only the dialogue for the main assembly line and the part specification for parts C, D, and L is included in Figure 3.

2.5 Automatic Code Generator

The code generator is a program that combines the responses to the user interface that results in the problem specification with the appropriate GPSS simulation macros and then automatically writes the corresponding GPSS simulation code of the manufacturing process. The code generator program is written in LISP on a Symbolics 3620 and consists of 250 lines of code and 39 rules.

Figure 4 is a partial listing of the GPSS code generated by the AMPS system. Lines 2770-3100 are the GPSS code for the assembly and two subassembly lines. Line 2820 is the transfer to the assembly station subroutine ASM. Line 2840 is the transfer to the task subroutine TASK. Lines 4280-4550 are the GPSS code for the manufacturing cell marco MFG. The extensive use of indirect addressing and MX$ require a large number of matrix savevalues.

The GPSS program for the manufacturing system in Figure 1 consists of 344 blocks. Of this total, 110 blocks were the macros, 25 blocks were the main program and 209 blocks were for defining the system attributes from the user interface program.

```
2770 *****************************************
2780 *       ASSEMBLY LINE x
2790 *****************************************
2800            GENERATE      V$TIME1
2810            ASSIGN        2,1
2820            TRANSFER      SBR,ASM,RTRN1
2830            ASSIGN        2,2
2840            TRANSFER      SBR,TASK,RTRN1
2850            ASSIGN        2,3
2860            TRANSFER      SBR,ASM,RTRN1
2870            ASSIGN        2,4
2880            TRANSFER      SBR,INSP,RTRN1
2890            ENTER         PA_a,1
2900            TERMINATE
2910 *****************************************
2920 *       ASSEMBLY LINE y
2930 *****************************************
2940            GENERATE      V$TIME5
2950            ASSIGN        2,5
2960            TRANSFER      SBR,ASM,RTRN1
2970            ASSIGN        2,6
2980            TRANSFER      SBR,TASK,RTRN1
2990            ENTER         PA_b,1
3000            TERMINATE
3010 *****************************************
3020 *       ASSEMBLY LINE z
3030 *****************************************
3040            GENERATE      V$TIME6
3050            ASSIGN        2,7
3060            TRANSFER      SBR,ASM,RTRN1
3070            ASSIGN        2,8
3080            TRANSFER      SBR,ASM,RTRN1
3090            ENTER         PA_d,1
3100            TERMINATE
```

```
4280 *****************************************
4290 *          MANUFACTURING CELL            *
4300 *****************************************
4310 MFG    ASSIGN        13,MX$CELL(P12,1)
4320        ASSIGN        14,MX$CTIME(P12,1)
4330        ASSIGN        16,MX$CTIME(P12,2)
4340        QUEUE         P13
4350        ASSIGN        7,MX$CSIZE(P12,1)
4360 CARTQ  ASSIGN        17,MX$ITEM(P12,1)
4370        ASSIGN        8,0
4380        ASSIGN        9,1
4390 PARTQ  ASSIGN        8+,2
4400        ASSIGN        9+,2
4410        ASSIGN        5,MX$ITEM(P12,P8)
4420        ASSIGN        10,MX$PART(P5,1)
4430        ASSIGN        20,MX$ITEM(P12,P9)
4440        QUEUE         P10
4450        TRANSFER      SBR,TAKEP,RTRN2
4460        DEPART        P10
4470        LOOP          17,PARTQ
4480        LOOP          7,CARTQ
4490 FAC    SEIZE         P13
4500        ADVANCE       V*14
4510        ADVANCE       V$MTIME
4520 MTIME  FVARIABLE     V*16#MX$CSIZE(P12,1)
4530        DEPART        P13
4540        RELEASE       P13
4550        TRANSFER      P,RTRN3,1
```

Figure 4. Partial listing of GPSS code

```
*********************
*   Create a line   *
*********************

1. Name of line: x
2. Number of stations: 4
3. Source of line:
     Type (see menu for selection): Beginning node
     Distribution: Exponential
     Mean: 300
4. Destination of line: Terminal
5. Name of the product of the line x: a

Do you want to modify the input above?(Y or N) No.

station 1
 (1) Station id: 1
 (2) Type of station: Assembly station
 (3) Station name: assy1
 (4) Part required:
     Number of part types required: 2

       Name of part: b
       Number of part: 3
       Name of part: c
       Number of part: 2
 (5) Time:
     Distribution: Normal
     Mean: 300
     Standard deviation: 10

Do you want to modify the input above?(Y or N) No.

station 2
 (1) Station id: 2
 (2) Type of station: Task station
 (3) Station name: task2
 (4) Time:
     Distribution: Normal
     Mean: 300
     Standard deviation: 10

Do you want to modify the input above?(Y or N) No.

station 3
 (1) Station id: 3
 (2) Type of station: Assembly station
 (3) Station name: assy3
 (4) Part required:
     Number of part types required: 1

       Name of part: d
       Number of part: 4
 (5) Time:
     Distribution: Normal
     Mean: 300
     Standard deviation: 10

Do you want to modify the input above?(Y or N) No.

station 4
 (1) Station id: 4
 (2) Type of station: Inspection station
 (3) Station name: insp4
 (4) Name of the inspection station substation: inspector
 (5) Name of repair station substation: inspector
 (6) Name of the place for scrap parts: scrap4
 (7) Time for inspection:
     Distribution: Normal
     Mean: 50
     Standard deviation: 5
 (8) Time for repair:
     Distribution: Normal
     Mean: 400
     Standard deviation: 10
 (9) Inspection rate (between 0 and 1 ): 1
(10) Reject (repair) rate (between 0 and 1): .2
(11) Scrap rate (between 0 and 1): .5

Do you want to modify the input above?(Y or N) No.
End of line x
Any more line to create? (Y or N) Yes.
```

```
****************************
*   Part specification     *
****************************

Part C
1. Part-id: 3
2. Part-name: PA_C
3. Supply-system: Pull from an inside source
4. Capacity and initial inventory at the stock points:

   Mximum cart capacity (max. number of parts per cart):
                                                    10

   Current cart capacity (number of parts per cart): 4

   Maximum number of carts at demand stock point: 10

   Initial number of carts at demand stock point: 4

   Maximum number of carts at supply stock point: 10

   Initial number of carts at supply stock point: 4

5. Vehicle used to move carts between stock points:
     Name: truck1
     Time:
     Distribution: Uniform
     Minimum: 8
     Maximum: 12
6. Source-where the part is made:
     (1) Manufacturing cell: mc1
7. Items required to make the part:
     Number of item types required: 1

       Name of item: i
       Number of item: 2
8. Set up time for each cart:
     Distribution: Constant
     Constant: 0
9.Time to make a part:
     Distribution: Normal
     Mean: 30
     Standard deviation: 3

Do you want to modify the input above?(Y or N) No.

Part D
1. Part-id: 4
2. Part-name: PA_D
3. Supply-system: Push
4. Capacity and initial inventory at the stock points:

   Maximum number of parts at stock point: 2000

   Initial number of parts at stock point: 64

Do you want to modify the input above?(Y or N) No.

Part L
1. Part-id: 12
2. Part-name: PA_L
3. Supply-system: Pull from an outside source
4. Capacity and initial inventory at the stock points:
   Maximum number of parts at stock point: 10000

   Initial number of parts at stock point: 10000
```

Figure 3. Partial AMPS interactive user interface dialogue

3.0 SYSTEM OVERVIEW

Figure 5 is an overview of the AMPS system. Once the user has scoped the problem domain, the user sits at the Symbolics 3620 and responds to the questions from the interface program. Based on the responses, the interface program creates an internal problem specification file. This file includes the manufacturing process network flow and the attributes for all the stations, cells and stock points. For example, some of these attributes are names; mean times and distributions; inventory levels and control strategies; inspection, failure and reject levels; and manufacturing conditions.

The problem specification file is then used as input to the automatic code generator program. Once the user has completed the interactive dialogue and has defined the manufacturing process, the automatic code generator generates the simulation program in the target language GPSS/PC. The output of the code generator is a GPSS program file which is then downloaded to an IBM PC class machine.

The GPSS/PC system is resident on the PC. The user then adds the experiment frame, such as the run statements, and the GPSS simulation program is executed. The output file is stored on a diskette or printed on the PC. To change the GPSS model, the user returns to the Symbolics 3620 and recalls the problem specification. The user interface then provides the user with a number of options to change or modify the problem specification. The code generator will then rewrite the GPSS program.

The AMPS system has been successfully ported to the Texas Instruments Explorer. However, some of the LISP statements are different between the machines. Therefore, several changes were made to the code before executing the AMPS system on the Explorer.

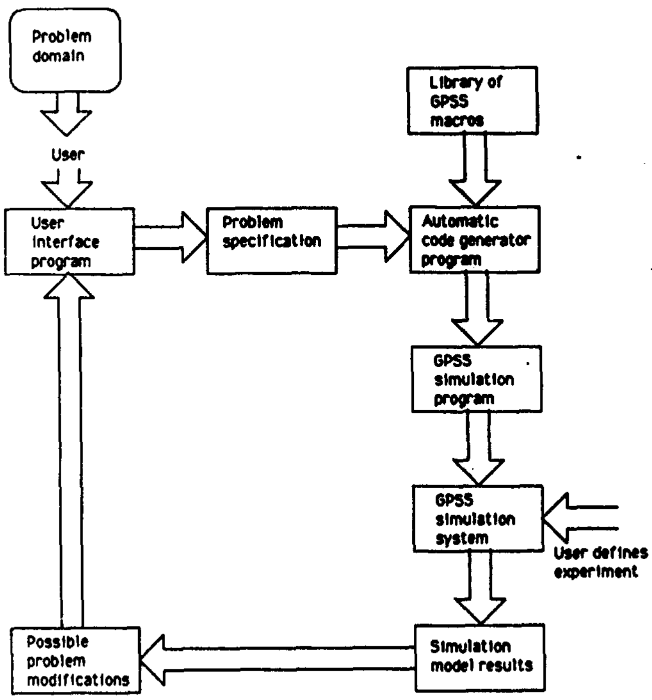

Figure 5. AMPS system overview

4.0 CONCLUSIONS

In summary, the Automatic Manufacturing Programming System (AMPS) is a fully operational system. The system is capable of modeling a variety of manufacturing problems provided the problems domain can be represented by the existing five manufacturing functions of assembly, fabrication, inspection, inventory transfer and a simple operation. The GPSS macros that have been written for these manufacturing functions are both the strength and weaknesses of AMPS. The strength is that with these macros the automatic GPSS code generation is a relatively straightforward task. The weakness is the robustness of these macros to adequately represent the domain of manufacturing functions. It is anticipated that many additional macros will eventually need development.

The system has been used to model several manufacturing processes and has modeled these processes quickly and accurately. The basic AMPS system structure has been used to model a 27 station manufacturing cell that makes four different part types with each part type requiring 47, 31, 22 and 22 operations respectively (Schroer 1988). The manufacturing cell was sufficiently different to exclude the interactive user interface and the automatic code generator. However, the concept of the library of macros was used for writing GPSS macros and for defining and inputing the station attributes. A benefit resulting from the use of the AMPS system is a very structured GPSS simulation code format that is easy to read and trace, not only by the modeler, but also by other team members. Also, the GPSS code generated by AMPS ran the first time with no syntax errors.

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Algorithm for Display of Automated Nondestructive Thickness Measurements

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ABSTRACT

Automating the manufacturing processes in any environment, whether its a complex aerospace structure or a simple mechanical part, requires defining normal human judgments such that computer-based processing can perform the same function. In automating robotics installations, there is a need for defining contours which are representative of some physical feature of the object of interest. Ordinarily these operations are considered in terms of machine vision operations. The work presented here demonstrates the use of such technology for defining thickness measurements obtained through robotic ultrasonic scanning of aerospace components.

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Session VII Program B

Artificial Intelligence and Expert Systems II

Chair: Bernard Schroer, University of Alabama in Huntsville

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A PLANNER FOR THREAT ASSESSMENT AND RESPONSE

1 May 1988

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ABSTRACT

This paper reports on a concept for an automatic planning system to coordinate assets for the self-protection of a combat aircraft. The planner will adapt to dynamic and uncertain mission situations by assembling response plans in a hierarchical fashion. Long-term plans are sketched in general terms using default estimates of performance. More specific plans are assembled incrementally as needed, by activating lower-level planners.

1. THREAT ASSESSMENT/RESPONSE SYSTEM ARCHITECTURE

The Planner discussed in this paper is an element of a conceptual Threat Assessment/Response system described in [15,16]. That system is being developed as an independent research effort in response to a generic need to integrate situation assessment, planning and control functions in tactical aircraft.

Key challenges in managing an aircraft's self-protection in combat are to develop automatic, real-time techniques which will (a) plan the assignments of sensors, countermeasures and evasive/avoidance maneuvers, given the uncertainties in threat assessments and in response effectiveness; (b) permit graceful recovery/replannning as new information becomes available; (c) schedule actions within time constraints for effective results; (d) coordinate the use of sensors to reduce uncertainties as required for response planning and cueing; and (e) resolve conflicting demands on assets in the interest of global utility.

Threat assessment functions (a) estimate threat identity, lethality and intent on the basis of available sensor and intelligence data and (b) predict the time to critical events in threat engagements (e.g. target acquisition, tracking, weapon launch, impact).

Response management functions develop and implement defensive plans of action by (a) selecting candidate responses to reported threat situations; (b) estimating the effects of candidate actions on survival; and (c) coordinating the assignment of sensors, weapons and countermeasures with the flight plan.

2. SURVIVABILITY RELATIONSHIPS FOR THREAT RESPONSE PLANNING

Payoff and cost functions in the present application are defined in terms of impact on the survival of the aircraft and on the attainment of mission objectives. We employ a survivability model based on that used by JTCG/AS, in which survivability factors are related to force-level measures of mission effectiveness [4]. In particular, we identify payoff and cost factors in an offensive mission (e.g. air strike, offensive sweep, defense suppression) as measures of mission attainment survivability (MAS), by means of the following definitional hierarchy.

2.1. Encounter survivability

The likelihood of the aircraft surviving an encounter with a given threat system is given by

$$P_{s/e} = 1-P_{tse}+P_{tse}(1-P_{ssk})^{m};$$

where

P_{ssk} = Probability of single shot kill;

P_{tse} = Probability of engagement by a threat system;
= $P_{detect} \cdot P_{assign|detect} \cdot P_{track|assign}$;

m = Number of shots fired at aircraft by threat.

2.2. Sortie survivability

The likelihood of the aircraft surviving the mission is defined as a function of encounter survivability:

$$P_{s/s} = \prod_{n} \exp[-ZDE(1-P_{s/e_{n}})];$$

where

ZDE = Zone density effectiveness; i.e. the probability of the aircraft's entering the lethal zone of a counter-air threat system.

2.3. Mission attainment survivability

Mission attainment survivability relates the above survivability factors to the attainment of force-level mission objectives; i.e. the destruction of intended targets:

$$MAS = 1 - \sqrt{1-[(1-P_{s/s})/P_{k/s}](G_o/S_o)^{2}};$$

where

$P_{k/s}$ = Probability of kill of threat target by aircraft per sortie;

G_o = Threat force size to be destroyed (mission objective);

S_o = Own aircraft force size.

In general, the goal of a self-defense system is to maximize $P_{s/s}$ within constraints on MAS.

3. ADAPTIVE PLANNING

There has been a fair amount of work in developing adaptive planning architectures [1,5,6,8], whereby a rough long-term plan is generated, to be modified and developed in detail as needed. Such an architecture has the obvious benefit of reducing the computational expense of developing fully detailed long-term plans in an application in which plans are subject to considerable adaptive revision.

The architecture of an adaptive planner should order the problem solving actions in a way which improves control decisions.

Such a system sketches out a long-term plan as a sequence of intermediate goals, incrementally forming detailed sequences of actions to achieve each intermediate goal as the need for such a decision arises. Control decisions are adaptively refined in such a planner; intermediate goals are ordered such that the results of early actions are likely to reduce the uncertainty about how to and whether to pursue later intermediate goals.

As Durfee and Lesser [5] note, these considerations indicate a planning process which favors (a) less costly intermediate goals; (b) discriminating intermediate goals; and (c) common intermediate goals; postponing decisions concerning longer term goals. Item (c) is an application of Stefik's [12] concept of least commitment planning and is key to planning in uncertain environments.

4. HIERARCHICAL IMPLEMENTATION

We submit that the desired adaptivity is attainable by means of a hierarchical planning architecture. In such an implementation, a planner generates and evaluates plans in a hierarchichal fashion; iteratively defining sequences of actions in pursuit of its higher-level goals.

In the self-protection system application, the global goal is that of maximizing sortie survivability ($P_{s/s}$) while achieving mission objectives. At each level in the plan hierarchy, sequences of subgoals are constructed in order to achieve the goal passed down by the next higher level.

4.1. Planning Hierarchy

The Planner is conceived as an object-oriented structure, involving a hierarchy of independent Planning Objects. Each such object is responsible for constructing and evaluating candidate action sequences in pursuit of its specific type of goal as illustrated in Figure 1 (see [10,13,14] on countermeasures modeling).

Although details of the lower planning levels will vary depending upon the system's type of mission and configuration (and therefore its repertoire of responses), a self-protect planner for a tactical aircraft will operate in pursuit of one or another of the following encounter-level goals as defined by the mission-level planner:

a. Preventing or terminating engagement by a particular threat system; e.g. avoiding the threat by flight path modification; using countermeasures to deny the threat target acquisition; or using weapons to eliminate the threat.

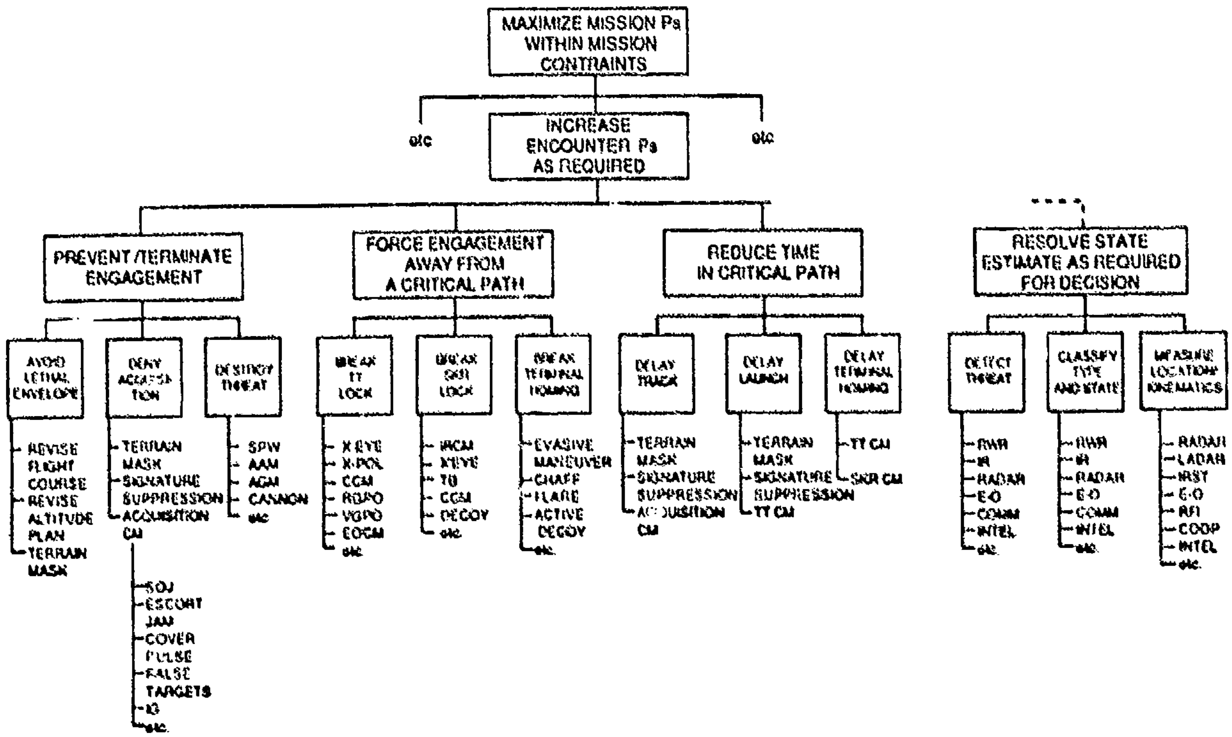

Figure 1. Representative Plan Hierarchy for Aircraft Self-Protection System

b. Forcing an engagement away from a critical (i.e. lethal) path; e.g. using TT countermeasures prelaunch or mid-course to break tracker lock or using seeker countermeasures to break seeker lock; or using terminal evasion and/or off-board countermeasures to break terminal homing.

c. Reducing the time in a critical path, so as to reduce the likelihood of a critical state transition; e.g. using break-lock techniques to delay a launch, reducing the time available to the threat to achieve a successful launch; delaying tracking (reducing the integration time available for the threat's fire control solution); or delaying launch or terminal homing to limit the available part of a missile's kinetic envelope (thereby providing maximum advantage for mid-course and terminal countermeasures).

A fourth family of Planning Objects pursue information acquisition. These may be tasked to support response planning at any level. Sensors and associated processing functions are allocated so as to resolve the system's estimate of the current world state or of predicted future states as necessary to improve the confidence in a response decision (see Section 5 below).

4.2. Mission-Level (Long-Term) Planning

The Planner develops and maintains a schedule of expected events and planned responses for assuring sortie survivability consistent with MAS. The schedule is developed based on a current mission flight plan and estimated threat deployment. A high-level response plan is developed on mission start. Mission-level re-planning occurs when there is a change in flight plan, on declaration of a new threat track and on resolution of a threat track location (i.e. when the estimated location accuracy falls below a reporting threshold).

The Planner develops rough long-term plans efficiently by foregoing appeals to lower level Planning Objects wherever possible; substituting default values for the data which would otherwise be returned by lower level planning.

The depth of planning employed is controlled based on current need and resource availability. Default, "canned" plan segments are implemented when either

a. time is not available for more refined planning (e.g. when a critical state transition is predicted requiring rapid response);

b. all available means of adaptive planning have been exhausted (e.g. at the bottom of the Planner hierarchy); or

c. the certainty in the default plan's results is sufficient for the particular goal at hand (e.g. in long-term planning); where predictive certainty is understood in terms of mass of evidence:

$$\sum_{x \in X} (pls(x)-spt(x)) \cdot (t_{max}(x)-t_{min}(x));$$

for the set of possible outcomes X.

4.3. Planning Object Operation

With each descending level, Planning Objects function as increasingly local experts. A lower-level planner constructs plans of action in pursuit of local goals which the higher-level planners have determined its expertise to be applicable.

A higher-level Planning Object will often task several subordinates to propose candidate plans in pursuit of the same goal. These competing plans become the resources by which the higher planner in turn composes its plan for achieving its more general goal.

In this way, the expertise required by any given planner may be limited both in scope and in depth. Thus, higher-level planners are able to deal abstractly with the more detailed plans of their subordinates; being concerned only with estimated payoffs and costs, rather than with details of implementation.

At each level in the Planner hierarchy each candidate Planning Object develops and evaluates a sequence of actions in pursuit of a goal handed down by the next higher planning level. If a nominated level n action is not further decomposable into yet lower level actions (i.e. it is an atomic action within the Planner repertoire), the corresponding Planning Object returns an estimate of the action's ability to achieve the goal for which it was nominated.

Otherwise, the level **n** Planning Object nominates a sequence of level **n+1** actions which, based on previously stored general plans, has an a priori likelihood of achieving the given level **n** goal [1].

The Planning Object for a candidate action receives (a) a resource budget (e.g. available time window, jammer or receiver duty factor, transmitter power); (b) the situation assessment information available for controlling the action; and (c) an assigned goal. Such a goal might be to avoid the lethal envelope of threat object z; or to delay launch by object z by at least t seconds; or to break seeker lock of object z.

Situation assessment information is in the form of sets of conditional event assertions. In the case of future events, these become event predictions. An assertion of an event of type x occuring at time t may be stated as

$$Pr(occ(x,t) \mid \tau); \tag{1}$$

where τ is a Boolean combination of statements in the form 'occ(x',t')' (cf. [2, 7,17]). As an example, τ may postulate that our system executes a plan: $\tau \equiv occ(\alpha)$, where α is a sequence of action instances $\{\langle a_0, t_0\rangle, \cdots, \langle a_n, t_n\rangle\}$. We model uncertainty in the time of events (as distinguished from the likelihood of their occurence) by construing event likelihood as a time-varying function.

Adapting an Evidential Reasoning formulation of likelihood and a convenient fiction that probability density functions are rectangular with time, we generalize (1) as (2):

$$\tau \rightarrow . \; \exists t \exists p[occ(x,t,p) \; . \; t \in [t_{min}, t_{max}] \; . \; p \in [spt, pls]; \tag{2}$$

for some $t_0 \leq t_{min} \leq t_{max}$, $0 \leq spt \leq pls \leq 1$.

That is, if τ, then event x will occur within the time interval $[t_{min}, t_{max}]$ with a likelihood which is within the interval [spt, pls], where spt and pls are evidential support and plausibility values per Shafer [11].

Upon activation, a Planning Object returns a proposed action sequence, together with an estimate of the likelihood of achieving the given goal if that action sequence is implemented. Each sequence element contains the following attributes:

a. Resource to be employed;

b. Time constraints (i.e. time window, technique duration and duty factor as applicable);

c. Side-effects (i.e. factors which may conflict with other plan elements):

(1) aircraft flight path change;
(2) aircraft signature change;
(3) percent utilization of resources;
(4) potential sensor interference (by spectral band and sector) and percent degradation;

A typical assertion of candidate technique effectiveness might have the form:

$$occ(cm(h,z),t_0,1) \; . \; type(z,k) \; . \; type(z,k) \; . \; state(z,s_1,t_0) \; . \rightarrow . \; \exists t \exists p(occ(start(s_2,z),t,p) \; . \; t \in [t_0+5, t_0+8] \; . \; p \in [0.8, 1.0]); \tag{3}$$

i.e. technique h, when applied against a system z of type k in state s_1, has an 80-100% likelihood of resulting in a transition to state s_2 within 5-8 seconds.

Upon receiving such proposals from its subordinate level n+1 Planning Objects, a nominated level n Planning Object employs a constraint propagation procedure (described in Section 7) to assemble an action sequence which, given the available resources and information reported by the subordinate candidates, will approach its own goal.

5. SENSOR/RESPONSE COORDINATION

Information acquisition actions may be invoked by Planning Objects at any level whenever that object determines that there is insufficient resolution in the system's world model to predict the results of its candidate actions with the confidence demanded by the tasking Planning Object. There have been several concepts reported in the literature for integrating information collection actions into planning [3,6,8,14]. Evaluating information acquisition plans requires determining the contribution which a given information element makes to the response decision process in a particular circumstance and on the conditional utility of each response decision available in that circumstance [14].

Generally speaking, sensors are assigned in pursuit of one or another of the following four goals:

a. To acquire new information which may require generation of a new plan segment (e.g. searching for new threats or for unanticipated weapon launch);

b. To resolve the decision of selecting among candidate plan segments; the goal being to reduce the uncertainty in the net payoff associated with candidate plan segments (e.g. determination of threat type and state);

c. To monitor plan execution for information which might warrant plan revision; e.g. monitoring countermeasure effectiveness for possible selection of alternative techniques (such as using terminal countermeasures if midcourse pull-off techniques are likely to be unsuccessful); and

d. To feedback technique effectiveness data for adapting countermeasure timing and control (e.g. in phenomenological or "surgical" countermeasures). Only some types of situation assessment hypotheses warrent continuous monitoring. Those asserting states having some persistence need only be verified at the time of establishment and at the time of use [3].

6. PLAN EVALUATION

Candidate plan segments are evaluated based on their estimated net impact on sortie and mission attainment survivabilty.

Table 1 lists the goals of various encounter-level action plans in terms of

Table 1. Survivability Effects of Planned Actions

ENCOUNTER-LEVEL ACTION/GOAL	MAS COST FACTOR				
	ZDE	P_{tse}	m	P_{ssk}	$1 - P_{k/s}$
Avoid Lethal Envelope	-				
Deny Acquisition		-			
Destroy Threat		-			-
TTCM (pre-launch)			-	-	
TTCM (mid-course)				-	
Skr CM (mid-course)				-	
Terminal CM				-	

their intended impact on mission survivability factors. For sake of consistency, we have presented such effects as negative impacts on various cost factors of MAS. Individual lower-level techniques for implementing such action plans will have functional specifications in the corresponding table locations, allowing quantification of technique effectiveness in specific situations.

Table 2 shows various side-effects characteristic of response techniques; Resulting impact on MAS cost factors are given in Table 3. Secondary or occasional factors are noted parenthetically [13,14].

Table 2. Side Effects of Planned Actions

ENCOUNTER-LEVEL ACTION/GOAL	ACTION SIDE EFFECT: Flight Path Change	Signature Increase	Asset Utilization	Resource Depletion	Sensor Interference
Avoid Lethal Envelope	X	(X)		X	
Deny Acquisition	X	X			X
Destroy Threat		(X)	X		
TTCM (pre-launch)		X	X		(X)
TTCM (mid-course)		X			(X)
Skr CM (mid-course)		X	X		(X)
Terminal CM	X	X	X	X	(X)

Table 3. Side Effect Impacts on Survivability Factors

ACTION SIDE EFFECT	MAS COST FACTOR: ΣDE	P_{tse}	m	P_{ssk}	$1 - P_{k/s}$
Flight Path Change	±				+
Signature Increase		+	(+)	+	
Asset Utilization					
a. Pre-launch CM		+	+		
b. Post-launch CM				+	
Resource Depletion					
a. Expendable CM				+	
b. Munitions/Fuel					+
Sensor Interference	(+)	(+)	(+)	(+)	(+)

7. PLAN ASSEMBLY

Each Planning Object assembles composite plans by selecting and adapting candidate plans provided by its subordinate Planning Objects.

In assembling a composite plan, a given level **n** Planning Object first orders the selected level **n+1** plans on the basis of stringency of time constraints; so that more flexible plans can be fit around those with very specific time windows for effective implementation. Given this ordering, a candidate composite schedule is generated; each succeeding plan candidate being fit into available time periods left by the already scheduled candidates.

This process recognizes that timing is more critical for some resource assignments than for others. Certain electronic countermeasures techniques have stringent requirements for time duration, duty factor and repetition cycle in order to be effective. Some measurement and countermeasure techniques are most effective if synchronized with the target phenomena. Other measurement techniques have only general requirements for update rates.

If conflicts - i.e. contentions for asset assignments - arise among the lower level candidate plans, the following procedures are invoked to achieve an internally consistent plan which approaches the composite goal:

a. slide candidate actions within their respective time windows, to allow the remaining candidates to be "shoe-horned" in;

b. beginning with candidates with least net payoff, reactivate the corresponding lower-level Planning Object for a different (and, in general, locally less effective) candidate plan;

c. beginning with candidates with the least net payoff, suppress candidate plans **m** at a time from the proposed plan set' where **m** = 1,2,···,**M**, for the **M** candidate plans.

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A ROBOTIC VEHICLE ROUTE PLANNER FOR THE 1990S.

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ABSTRACT

During the 1990s, automated (robotic) vehicles will take over the labor-intensive and hazardous tasks vehicles are asked to accomplish. The U.S. military has already designated up to 40 vehicle missions to be accomplished by automated vehicles. In addition to the military, industry is also looking for automated vehicles to perform automated-movement tasks. Thus the need has clearly been established and new contracts for these vehicles are continually being awarded.

Vehicles designed to perform these tasks must have a global route planner that chooses the route the vehicles are to traverse. Also aboard the vehicles there must be a navigation system that confirms that the vehicles are following the desired route. While the military applications of this technology are generally off-road, the over-all objective is to gradually move this technology to the civilian arena for the guidance of automobiles and trucks on the nation's highways.

In addition to the topics identified above, this paper will also describe the data base inputs required by the global route planner, the difficulties associated with moving from off-road to on-road operation, and the requirements on the navigation system.

INTRODUCTION/SUMMARY

The next decade will see the introduction of many more robotic/automatic features into automobiles and military vehicles of all kinds. One such feature is a route planner. Since the need and the desire exist, there can be little doubt that this capability will be added to the design of future vehicles. The addition of these systems will make automobile driving, especially long distance driving, more enjoyable and probably safer. As a former chief engineer from Ford, Jerome Revard, once said, "Driving from

Detroit to Florida really isn't all that much fun."

This paper describes the need for a route planner, the general requirements for the route planner (including the data base requirements), the difficulties and the advantages associated with moving off-road operation to on-road operation and the advantages, the driver-machine interface and the navigation system requirements (including a summary of potential candidates).

What is envisioned for the 1990s are robotic vehicles that are controlled through teleoperated systems or are completely automatic. The first of these subsystems is already offered as an option on today's automobiles; we know it as "cruise control."

ROUTE PLANNER/PATH PLANNER

This paper is about a route planner, not a path planner. The distinction between the two is important since they perform different functions and therefore have different requirements. The route planner, sometimes referred to as a global route planner, plans routes for the vehicles out to the vehicles' destination or a designatable waypoint or checkpoint, e.g. 10 kilometers. This distance could be a fraction of a much larger trip, say 1,000 kilometers or 10,000 kilometers. On the other hand, a path planner is used to plan paths in the immediate vicinity of the vehicle, and has a path planning capability of 3 meters to 50 meters (9 feet to 150 feet). As the vehicle moves, this planning area proceeds with the vehicle, in front of it. The path planner works in conjunction with a local obstacle detector in determining which way the vehicle should go in this limited area. The local obstacle detector locates and identifies the obstacle, and the path planner, using expert rules, determines what path the vehicle should take. When the vehicle has cleared the obstacle, the global route planner (not the path planner) replans the route (not the path) to take the vehicle to the desired destination.

NEED

There are two types of identifiable needs for route planners at this time, military and civilian, both of which are associated with robotic vehicles. The military need will be discussed first since it is believed to be more pressing and immediate.

MILITARY - The military is proceeding quite rapidly in the area of robotic vehicles, especially in the use of Remotely Piloted Vehicles (RPVs) by the Air Force and Army and controlled submersibles by the Navy. The Army is investigating of the use of remotely controlled track and wheeled vehicles for a large number of mission uses. They have identified, as shown in Table 1, 20 missions where a robotic vehicle could or should be used to increase the probabilit: of success, increase the human survivability (although the vehicle survivability might decrease), and be more cost effective. The Army has a number of programs in development, including the Autonomous Ground Vehicle Technology (AGVT), the Robotic Obstacle Breaching Assault Tank (ROBAT), and the Robotic Command Center (RCC), which will be able to control

TABLE 1

ROBOTIC VEHICLE MILITARY MISSIONS

1. Reconnaissance - NBC (Nuclear, Biological, and Chemical)
2. Reconnaissance - Visual/IR - Scout
3. Surveillance - Stand Watch - Automated Sentry
4. Mine Laying
5. Mine Clearing - ROBAT
6. Obstacle Clearing
7. Decoys - Thermal
8. Decoys - Audio
9. Smoke Generator
10. Communications Relay
11. Electronic Warfare Jammer
12. Anti-Tank
13. Logistics Transporters - Ammunition
    - Fuel/POL (Petroleum, Oil, and Lubricant
    - General Cargo
14. Evacuate Wounded
15. Disposing of Unexploded Ordnance
16. Vehicle Recovery Operations
17. Weapons Carriers - Tanks
18. Weapons Carriers - Howitzers
19. Remote Targeting Command Post for Field Arti 'ery

up to four robotic slave vehicles. One of the possible solutions to the oft stated balance of forces problem, i.e., the tanks in Europe, would be through the use of robotic vehicles.

CIVILIAN - The civilian market for robotic vehicles, and hence robotic vehicle route planners, is just beginning to emerge. A recent public announcement by a vehicle development company stated that by 1989 they intended to be producing 25,000 vehicles per year for the physically handicapped. The significance of this is that the design of the controls used for this vehicle would be identical to that used on a robotic vehicle. For example, the vehicle would be joy-stick controlled with actuators, and sensors on the fuel control, brakes, and steering. To operate the vehicle from a remote location, using television, a communication link must be added and the joy-stick would be placed at the desired remote location.

The creation of a new consortium of the Transportation Departments of four states (Pennsylvania, Michigan, California, and Texas)and the Federal DOT is another indicator of the progress of robotic vehicle design. This consortium has been formed to research and define the requirements for the next generation of highway, which must interface with the next generation of automobile. In the past the interface between the automobile and the highway has been the bottom of the tire and the pavement. In the future the interface will be much more complex, with a number of sensors and transmitters being built into the future highways. These will be capable of interacting with and supplying information to those automobiles that have the subsystems to utilize the information. On expressways, the sensors could notify the driver of the up-coming exit and the distance and identification of the next exit - they could identify and notify drivers that a car going at a high rate of speed is approaching them from the rear or that a car, going the wrong way on the expressway, is approaching them. The systems on the cars could advise the driver if it is safe to change lanes, and could provide automatic braking when approaching any obstacle. The now-frequent slow downs for highway construction (single lane traffic) might be avoided if a driver is made aware of them. Nothing is more frustrating than to be caught, unsuspecting, in a waiting line after having by-passed an exit where one might have exited and avoided the wait.

ROUTE PLANNER REQUIREMENTS

The requirements for military and commercial route planners vary considerably. The military applications will require both on-road and off-road capability and, in general, the operational area is not as broad as in the commercial applications. The military area might be 10 kilometers by 20 kilometers. The commercial applications would be limited to on-road applications within an area (like a metropolitan city) of 60 kilometers by 60 kilometers. This expanded area for commercial requirements results in increased memory capacity for the route planner data base. This, however, can be resolved by providing additional memory on disks.

DATA BASE REQUIREMENTS

Again the data base requirements for the military and commercial applications vary considerably. The commercial applications, in their simplest form, might only require positions and locations of the streets. In fact, ETAK Corporation already has a system that utilizes this type of data base. The military systems, because of their off-road operation, must have a rather large array of data attributes to be useful. These should include soils, slope, elevation, vegetation, hydrology, linear features (including transportation lines like roads and railroad lines), cultural features, vehicle characteristics, enemy threat locations, friendly forces locations, and battle boundary lines. Off-the-road route planning is complicated by the need to acquire and evaluate this large amount of detailed data compared to on-the-road route planning. The commercial/civilian market has very little need for an off-the road route planner.

A whole paper could be devoted to the subject of resolution requirements of the data base attributes. The current DMA (Defense Mapping Agency) standard is 100 meters, with 30 meter resolution being obtainable from the digitization of USGS 1:24,000 paper maps. Resolutions of 5 meters are obtainable from SPOT(French) and USSR satellite image data. One of the real challenges in data base construction and route planner design is the combining of different attribute data bases with their differing resolutions and different pixel registrations. A preferred resolution would be one that approaches the width of a vehicle, i.e. 3 meters. This would provide the capability planning a military cross-country route that could go between trees where the stem spacing was 3 meters or greater. The vehicle would simply brush aside the branches and go on. Figure 1 shows an actual set of attributes and the resolutions obtainable for them. As shown not all the

FIGURE 1

Data Base Attributes

Data Source	Data Description: Elevation			Vegetation			Stem Spacing			Primary Surface Class			Secondary Surface Class			Linear Features		
	10m	30m	100m	10m	30m	100m	10m	30m	100m	10m	30m	100m	10m	30m	100m	10m	30m	100m
ERIM		W	X		W	X							W	X	X	W	X	X
ETL					W	X					W	X					W	X
Geo-Spectra	W	X	X															
WES			z			z			z			z						z
USGS (DLG)												z						z

W – data obtained and installed in data base
X – data installed via propagation
z – data obtained but not suitable

attributes included in the data base can be provided at as high a resolution as would be desired. Note that, only in the case of elevation, was 10 meter data obtained. Better resolution can be obtained at increased cost.

SYSTEM ARCHITECTURE APPROACH

One of the considerations in designing a route planner is the size of the area (width, breadth and depth) to be accommodated by the system architecture. All of these will affect the size of the computer memory and the executing time. The width and breath will probably be limited by the system memory. The executing time can be improved by determining the "cost" for traversing a pixel by utilizing large areas where the area is simple and uniform and decreasing smaller areas where the area is complex. The computer will have the ability to make a judgement about the proper size of the pixel to use.

NAVIGATION SYSTEM REQUIREMENTS

The navigation system on the vehicle must answer the question "Where am I?" for the system controller. The system controller will supply the destination, from which the route planner, will determine the route. Also to be supplied by the navigation system will be the vehicle he ng. The navigation system should also supply the distance to go and the heading of the next checkpoint. The route planner should divide the route into fairly straight line segments that can determine the checkpoints. Checkpoints should be a very visible landmarks that a teleoperator can identify, such as cross-roads and intersections, bridges, road changes of direction, cultural features (buildings etc.) and elevation changes (tops of hills or bottoms of valleys). A current military route planner provides checkpoints at water crossings and intersections. The accuracy of the navigation system should be at least 2% of the distance traveled and be capable of being updated en route as known locations are reached. The cost of the navigation system should be no more than $10,000 for the military version and $3,000 for the commercial version.

Table 2 shows a sample route planner output which is string of UTM (Universal Transverse Mercator) coordinates for a series of checkpoints that the route planner has selected. The navigation and guidance systems must assure that the vehicle passes through these checkpoints. Other characteristics of the path are also listed including accuracy, crossings, direction to the next checkpoint, type of road, and distance to the next checkpoint.

USE OF EXPERT KNOWLEDGE

Some expert rules have already been generated, such as, "avoid the deep water, avoid enemy threat areas, stay off steep slopes, and select the best route for the mission description." This can be done by changing the cost values on the individual pixels. As additional testing occurs, improved expert rules will surface and can be incorporated into the system design. Also as more and more personnel work with route planners they will generate and incorporate improved expert rules.

TABLE 2

Typical Route Planner Output

Site: KNOX UTMZone: 16 Mission ID: Mv-Cn Date: 5/04/88 Time:16:18:09

Planning Weights -- Trafficability: 65 Vulnerability: 5 Detectability: 30

Ckpt	E	N	Acc	Cross	Dir	RdTyp	Speed	Dist	Veget	PrSur	Threat	ID	DST	c/c
1	602850	4203800	±50	None.	315	Trail	48- 61	71	2	27	V 00 0			0
2	602800	4203850	±50	Trail	270	ltdRD	19- 61	441	1	27	V 00 0	149mc	1.9	30
3	602400	4203750	±50	Dirt	243	ltdRD	39- 60	1160	1	26	V 00 0	130mc	2.2	60
4	601450	4203400	±50	Trail	225	ltdRD	46- 61	583	1	26	V 00 0	116mc	2.7	60
5	600950	4203200	±50	Escrp	225	ltdRD	49- 61	241	7	28	V 00 0			60
6	600850	4203000	±50	None.	180	None.	19- 19	100	7	26	V 00 0			0
7	600850	4202900	±50	None.	167	Dirt	38- 58	1584	7	26	V 00 0	91mc	2.6	48
8	601189	4201561	±15	None.	213	None.	17- 20	72	7	26	V 00 0			0
9	601150	4201500	±50	None.	180	Dirt	38- 56	626	7	26	V 00 0	69mc	2.7	15
10	601050	4200900	±50	Dirt	167	ltdRD	4- 61	619	7	26	V 00 0			31
11	601504	4200541	±15	Strem	180	ltdRD	55- 57	30	7	26	V 00 0			0
12	601504	4200511	±15	Dirt	225	ltdRD	0- 61	1220	1	26	V 00 0			56
13	602035	4199835	±50	Dirt	206	ltdRD	54- 55	49	1	26	V 00 0			0
14	602014	4199791	±15	ltdRD	135	Dirt	54- 58	42	1	26	V 00 0			60
15	602044	4199761	±15	Strem	180	Dirt	29- 58	1919	1	27	V 00 0			58
16	602524	4198561	±15	None.	180	None.	16- 18	105	1	26	V 00 0			60
17	602524	4198456	±15											

CONCLUSIONS

Route planners as well as other electronic driver-assist devices will be incorporated into the design of both military and commercial land vehicles starting in the next decade.

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A DEMONSTRATION OF RETRO-TRAVERSE USING A SEMI-AUTONOMOUS LAND VEHICLE

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ABSTRACT

A Jeep Cherokee has been modified by Sandia National Laboratories to allow remote control either by teleoperation or through computer generated commands (autonomy). This vehicle has been used for development of hardware and software and in the demonstration of concepts for computer augmentation of remote controlled vehicles. As part of this activity, a system has been configured which allows an operator to teleoperate the vehicle from one location (home base) to another (destination). At the completion of teleoperation, the operator can instruct the vehicle to return to the starting position. The vehicle then autonomously performs a retro-traverse, reversing the path by which it reached its destination.

During teleoperation, operator commands are given through an operator control interface consisting of a steering wheel, brake and throttle pedals, and a video display. Commands are transmitted to the vehicle and video returned from the vehicle over RF communication links. Periodic way points are automatically recorded for later use by the vehicle system.

Navigation during retro-traverse utilizes dead-reckoning inputs from an odometer, compass and steering angle potentiometer. Way points (previously identified during teleoperation of the vehicle) are linked by short, straight line segments. Along each path segment, the control system generates the steering and speed commands necessary to direct the vehicle towards the next way point.

Retro-traverse has been demonstrated over open terrain at Sandia National Laboratories. Path following accuracy and final positional control is a function of dead-reckoning system limitations and control system design. These limitations are discussed, and an improved system is proposed.

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INTRODUCTION

Removing the operator from a land vehicle is desirable for many operational conditions, particularly those involving a hazardous environment or highly repetitive movements. Control of the vehicle can be performed either by an operator at a remote location (teleoperation) or through a computer-driven, autonomous system. A number of systems of both types have been constructed and tested at Sandia National Laboratories [1,2,3] as well as at other locations.

The general approach to design has been to develop systems which are either teleoperated or autonomous. A few attempts have been made to mix these two types of operation. The most ambitious of these is the Advanced Ground Vehicle Technology program [4,5], supported by the US Army Tank and Automotive Command (TACOM). In the AGVT demonstration systems, a vehicle with full teleoperation capabilities is combined with sufficient computational power to allow autonomous road following, path planning, and local obstacle avoidance. Much of the autonomous capability is drawn from the work of the DARPA Strategic Computing Program, Autonomous Land Vehicle Project [6,7].

An alternate approach has been developed in the Computer Aided Remote Driving (CARD) system [8]. In this system, the operator is asked to identify path points from viewing a three-dimensional video display of the area in front of the vehicle. Given the path points, a computer system provides commands to the vehicle to execute the indicated path. This type of operation actively combines the capabilities of the human operator with those of a digital computer. The operator is removed from the details of vehicle control and the computer is not required to perform the complex functions of detailed scene analysis, global path planning, and obstacle avoidance. Operation over selected path segments of up to 40 meters has been demonstrated.

The system developed at Sandia National Laboratories addresses the mix of teleoperation and autonomy through a mission sequential control transfer. That is, the initial course planning, maneuver generation, and obstacle avoidance are performed through teleoperation. At the conclusion of a mission, the vehicle autonomously returns to the start location by reversing the route already traveled. Since the route has been proven to be negotiable (during teleoperation) and has been plotted, the requirements placed on the autonomous navigation system are considerably simplified.

VEHICLE SYSTEM

An American Motors Corporation (AMC) Jeep Cherokee was used as the vehicle to be controlled [9]. This vehicle, shown in Figure 1, is a four-wheel drive 1980 Jeep Cherokee. It is equipped with a standard six cylinder engine and automatic transmission. An in-line floor shift was installed in place of the column-mounted gear shift. Electric actuators control the throttle, brake, gear shift, and steering. Actuator control is through an on-board 68000 microprocessor. Sensors have been installed on the Jeep to provide feedback on vehicle status. These sensors include actuator positions, vehicle velocity, distance traveled, inclinometers (to measure pitch and roll), and vehicle heading.

Navigation utilizes three of these sensors; heading, steering position, and odometer. Heading is read from a flux gate compass mounted on the top of the Jeep. This compass has a resolution of 0.2 degree and an accuracy of ±1 degree. Steering position is measured from the position of the vehicle steering gear tie-rod. A linear potentiometer provides steering position accurate to ±2 degrees.

The odometer used is a magnetic pulse system mounted on the drive shaft. This device provides distance traveled to a resolution of 0.3 feet. Being mounted on the drive shaft, the odometer effectively averages the distance traveled by both rear wheels. No compensation is added for wheel slip.

The vehicle control station was adapted from previously existing hardware. It is a three-bay rack (shown in Figure 2), with three 25 inch video monitors, a computer CRT, and a variety of communications and recording systems. An IBM AT is used as the main control station computer.

Driver input to the vehicle is through a steering wheel, throttle pedal and brake pedal. These are mounted on a movable column which can be adjusted for operator comfort. This setup has been found to be relatively easy to use when driving the Jeep in an off-road environment.

Primary outputs from the vehicle are video and digital sensor data. The video is derived from one of several different systems which can be mounted on the Jeep. These include a single fixed mount camera, multiple fixed cameras (arranged to provide a panoramic view), or a steering-slaved camera in which the camera pans with the vehicle steering. In all cases, a horizontal field-of-view (for each camera) of approximately 42 degrees is used.

Sensor data, including speed, heading, actuator position, and vehicle pitch and roll, are displayed on a CRT mounted in the driving station.

The vehicle and control station systems have been configured as a multipurpose test bed with power, cabling, communication, and multiple mounting points sufficient to support a variety of test requirements. The major experimentation to date included an extensive series of vision system tests [10] and the work presented here on retro-traverse.

CONTROL SOFTWARE

There are two major software systems used in controlling the Jeep. The first resides on board the vehicle and is dedicated to local control. This system is an assembly language program, used by the on-board 68000 processor to receive predefined ASCII commands from the remote console. It controls the vehicle driving functions and generates output from vehicle sensor data. Communication to the remote console is through a digital RF modem.

The second software system provides the operator interface, dead reckoning, and path-following algorithms. This system resides in an IBM AT mounted in the remote console.

Normal vehicle control (teleoperation) reads operator inputs from the driving station at the remote console, converts them to the appropriate command characters, and transmits them to the Jeep. Data from the Jeep is received, processed, and routed to the display. In addition to the direct driving commands, a variety of other commands are available to assist the operator. Single keystrokes (on the control keyboard) are required to center the steering, null the brake/throttle, or shift gears. In the case of the gearshift, full brake is automatically applied prior to sending the shift command. An emergency stop routine is also available.

Dead reckoning combines the inputs from the vehicle-mounted compass and odometer to generate a vehicle position relative to the starting location. Accuracy over a closed course averages approximately 4 percent of distance traveled. The present system utilizes time-sampled sensor readings. No filtering is performed, nor are turn-rate or wheel slip compensations included. There are currently no provisions for position updating from external reference inputs. Significant upgrades to this dead- reckoning system are planned.

Options for autonomous operation of the vehicle include map making, path following, and retro-traverse. Map making is accomplished during teleoperation by automatically saving position and heading data from the vehicle dead-reckoning navigation system at regular intervals along the path being traversed. Data is saved to disk upon command by the operator.

When path following or retro-traverse operation is desired, the operator identifies a specified map file. This file is loaded from disk into an array of path way points. If retro-traverse is to be performed, the order of points is inverted as the data is retrieved from disk. In addition, the requirement for a 180 degree turn is added as the first action to be executed. This positions the vehicle at the start of the retro-traverse path, headed in the correct direction to commence path following.

The path-following algorithm functions to control both vehicle speed and heading. Initially, a nominal speed is set for the vehicle. The path ahead of the vehicle is searched for turns which are checked for lateral acceleration at that speed. Vehicle speed is adjusted downward if necessary to keep lateral acceleration below a preselected maximum value. Speed is reset to the nominal value after the turn is executed.

Vehicle steering commands are calculated through a procedure which references vehicle heading and position with the desired current path segment heading and position. First, the difference in heading angle (bearing) between the vehicle and the current path segment is calculated and used as a steering input to bring the vehicle's heading parallel to the path. Vehicle position is then referenced to the desired position. If the vehicle is within a preselected minimum distance (dead band), no further perturbation of the steering is done. If the vehicle is outside of the dead band, the steering angle is adjusted to converge the vehicle path and the desired path. This sequence repeats as the vehicle moves from one path segment to the next. Simple proportional control is used throughout.

Future efforts are planned to improve the steering control sysem utilizing a more optimal control system design.

When the end of the path is sighted, the vehicle is decelerated to stop at or just before it reaches the end of the path.

EXPERIMENTATION

The Jeep has been teleoperated over a course previously used for vehicle mobility testing. This course consists of sections of improved dirt road intermixed with unimproved terrain. Figure 3 illustrates one off-road section. Three short sections of this course (each approximately 200 feet in length) have been used for retro-traverse testing. These sections met three criteria. First, a selection of straight and gently curved travel could be tested. Second, the terrain is open and fairly smooth. This minimizes errors in dead reckoning from wheel slip, vehicle tilt, etc. Third, on these course sections, vehicle positioning does not require extreme precision. There are no obstacles located in the immediate vicinity of the course so dead-reckoning system drift will not drive the vehicle into a hazardous position.

During the experimentation, each course segment was driven with the Jeep being controlled through teleoperation. Path data was stored immediately following each traverse. The vehicle was then manually positioned at the start of the course segment (for path following) or at the end of the segment (for retro-traverse). The autonomous software was engaged and the vehicle was allowed to follow the path under computer control. Multiple tests were conducted using the same recorded course segment data.

RESULTS AND DISCUSSION

The Jeep was able to successfully perform path following and retro-traverse operation over the 200 foot course segments shown in Figure 4. Twenty separate tests were performed. At the end of each test, the vehicle was within 10 feet of the desired end point.

Final position error can be divided into two components, dead- reckoning system drift and position control error. Dead-reckoning system drift contributes a low frequency error as the vehicle-estimated position slowly deviates from the true position. For the present system, drift is approximately 4 percent of distance traveled. Over the 200 foot course, errors in the range of 8 feet would be expected. Drift can be reduced through improved instrumentation and data processing but cannot be eliminated. Periodic updating is necessary to reset the dead-reckoning position to prevent these errors from growing without bound. The present system does not have an update capability so operational range is currently very limited.

Position control error results in a high frequency error (compared to dead-reckoning system drift) centered around the nominal path determined by the dead-reckoning system. This error is a function of the specific control system implementation, the capabilities of the Jeep actuators, and the effect of terrain on the Jeep path. For a well-designed control system, there should be no long term error accumulation, and the deviation from the nominal path should be small. The present implementation is a simple proportional control which, when coupled with the electric actuators on the vehicle, results in under-damped performance as shown in Figure 5. The average error (from the path determined by the dead-reckoning system) was less than 2 feet over the testing reported here. Improved actuators and a tighter control system are planned improvements.

This data graphically demonstrates the limitations of relying totally on navigation by dead reckoning. As the path gets longer, the vehicle positional error grows. The allowable error limits are a function of the terrain and mission. For example, if part of the route requires road following, only a very limited cross-range deviation can be allowed. Dead reckoning, by itself, cannot provide this accuracy over any appreciable distance. A number of different schemes for position updating are presently available. Examples include a variety of satellite position fixing systems, ground emplaced beacons, and active landmark identification. The appropriate update mechanism for retro-traverse is very dependent on the vehicle mission and operating environment and will be the subject of future work at Sandia National Laboratories.

The system, as configured for these tests, requires the use of the computer in the control station. This setup was developed to allow ease of programming and concurrent work on the control station and vehicle. It does, however, result in a need for constant communication between the Jeep and the control station. A future enhancement to the system will be to move the computations done on this computer to the vehicle. Transferring the storage of way point data, calculation of driving commands, and monitoring vehicle position to the vehicle will allow implementation of an automatic homing capability in the event of signal loss. This would be a desirable feature for many applications, since, in the event of communications loss, the vehicle would be able to return to the general vicinity of the start point for recovery and reuse.

There is no restriction on the relationship between start and end points in this implementation of retro-traverse. It is therefore possible to apply this system to autonomous operation on a closed course. After teleoperating the vehicle over the course, the retro-traverse could be engaged to provide autonomous travel around the loop. The dead-reckoning system would require periodic updating to maintain positional accuracy.

Obstacle detection is not required in the demonstrated route following because the planned route is assumed to be clear. This assumption is made because the vehicle traversed the route immediately prior to the retro-traverse operation. This may not be valid if the environment contains potential obstacles which are mobile (other vehicles, animals, etc.) if considerable time has elapsed since the first traverse, or if environmental conditions have changed. Further, if the route has significant roughness very near the route of travel or requires positional accuracy beyond the limits of the dead-reckoning system, obstacles may be encountered. It is most likely that some or all of these factors may be present in real applications. A local obstacle detection and avoidance system will therefore be required.

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Figure 1. Jeep Cherokee Test Vehicle

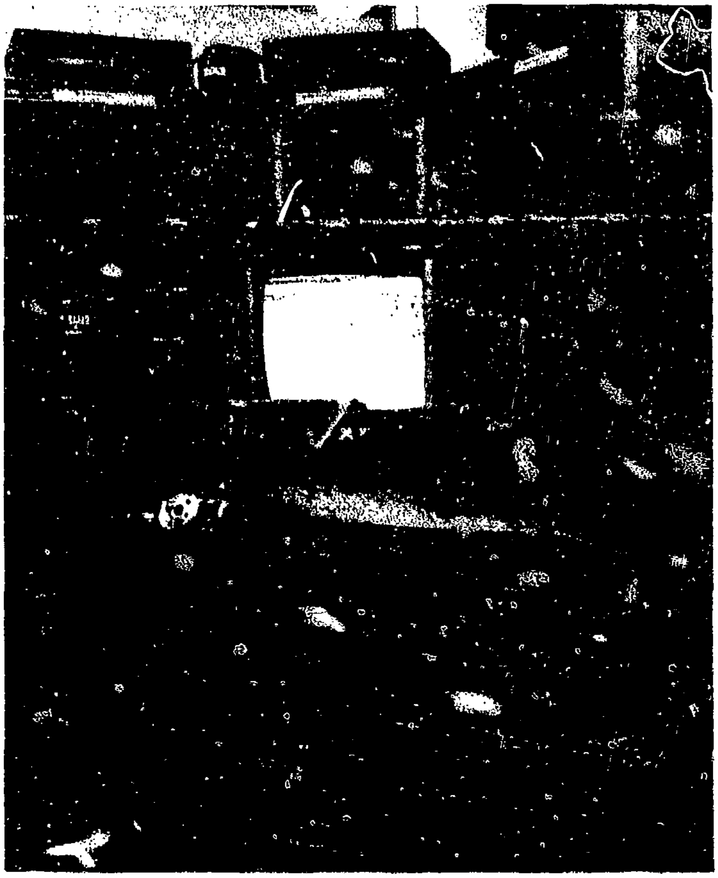

Figure 2. Teleoperation Control Station

Figure 3. Test Course Terrain

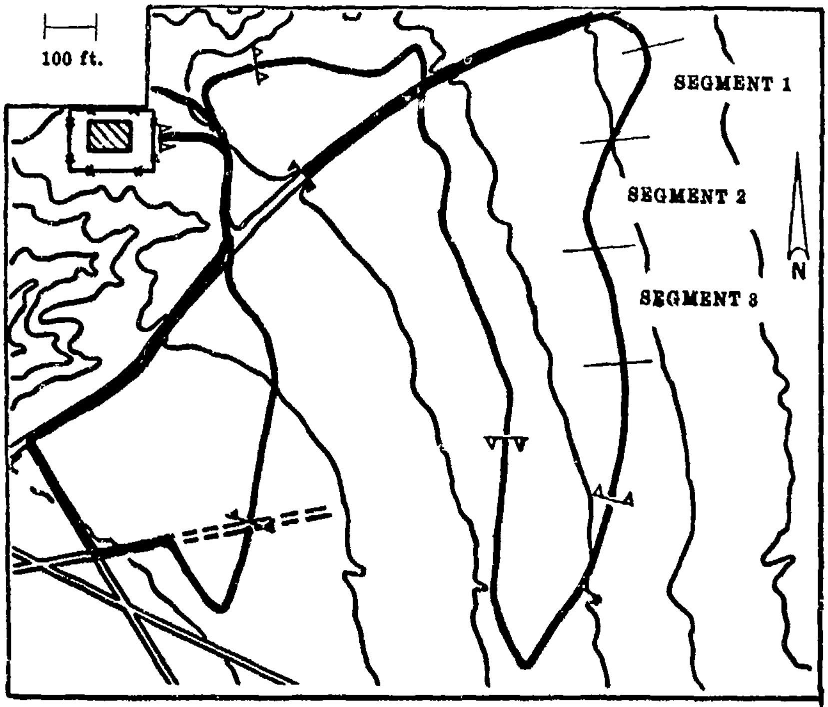

Figure 4. Test Course Segments

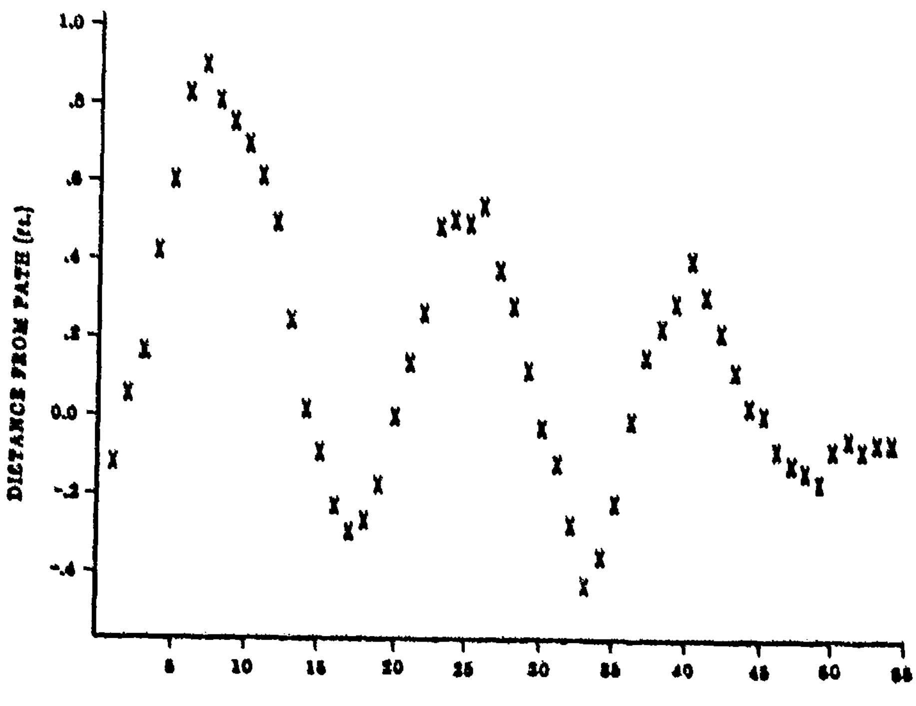

Figure 5. Control System Performance

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Dynamic Planning for Smart Weapons

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ABSTRACT

Under the sponsorship of DARPA and the U.S. Army, Martin Marietta is developing a demonstation of the avionics suite for a fully autonomous unmanned aircraft capable of seeking out and destroying hidden mobile targets deep behind enemy lines. This avionics suite has two major subsystems including perception and planning. The perception subsystem is responsible for recognizing targets and their possible hiding places during low-altitude flight using a combination of FLIR and millimeter-wave radar. The planning subsystem is responsible for maneuvering the vehicle so that as many perceived hiding places as possible can be examined in detail.

This paper focuses on the planning system and describes how it allows the vehicle to react swiftly and intelligently to percieved targets, clues, threats and obstacles in an every-chang ng dynamic environment. Special emphasis is placed upon how artificial intelligence technology and knowledge-based planning tecniques are being made compatible with real-time requirements.

The paper begins with a brief overview of the Smart Weapons concept of operations and its avionics suite. It then focuses in on the planning subsystem and its major components including mission management, dynamic planning, plan monitoring and plan execution. The functional design of each of these components is described in detail with emphasis on how they are being implemented in hardware and software for maximum real time performance. Finally, a detailed scenario is presented showing how the planning system responds during the fifteen seconds immediately following the discovery of a potential target.

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A Knowledge Representation Scheme for a Robotic Land Vehicle Route Planner

31 May 1988

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ABSTRACT

This paper describes knowledge representation schemes used on the Prototype Global Route Planner Project. The ultimate objective is to develop a military robotic vehicle route planner for missions covering several to tens of kilometers. The planner being developed uses a terrain database, vehicle data, and threat data, coupled with trafficability, vulnerability, and mission objective models.

The paper describes current efforts in vehicle mobility modelling and terrain data representation. Direct correlation between vehicle mobility characteristics and available terrain data is required for accurate mobility prediction. A combined approach using the Cross-country Movement (CCM) model of DMA and expert derived knowledge represented in an object-based AI model is explained. Likewise, vulnerability of a potential route is assessed during the planning activity using basic threat algorithms combined with expert-derived knowledge represented in an object-based AI model. Trafficability and vulnerability considerations are weighted appropriately by the mission objective models, also derived through expert consultation. Finally, problems encountered with current terrain databases, mobility models, and representation schemes are discussed.

1.0 Introduction

The Prototype Global Route Planner (PGRP) was developed to provide an automated method of planning cross-country routes on the order of 10 km long. The planned routes will supplied to an autonomous robotic vehicle in the form of direction and speed commands. From this information, the autonomous robotic vehicle would rely n an internal navigation system and route following sensors to negotiate the complete route. Although there are no firm requirements as such, the PGRP could eventually work in conjunction with vehicles such as the Autonomous Ground Vehicle Technology (AGVT) vehicles, the Autonomous Land Vehicle (ALV), and the Robotic Command Center (RCC).

The PGRP is required to demonstate path planning over a variety of terrains and using a variety of mission objectives and vehicles. Specifically, PGRP is to be demonstrated at Ft. Knox, KY and Camp Grayling, MI in field tests using an M113 and a HMMWV. Mission scenarios and threat types associated with four missions (reconnaissance, vehicle recovery, wounded recovery, and movement to contact), are to be planned and demonstrated. The system is to use terrain data of resolutions expected to be operational through the 1990's (100 meter to 10 meter).

2.0 Description of the PGRP System

The PGRP system architecture is shown in figure 1. The terrain database is a complete description of the aspects of the terrain that are important in the assessment of trafficability and vulnerability. The terrain database is not an existing product of any one government or private agency, but is rather a combination of many existing terrain databases as well as digitized data from existing maps. The development of the PGRP terrain database and efforts by DOD towards a singular database are not the subject of this paper.

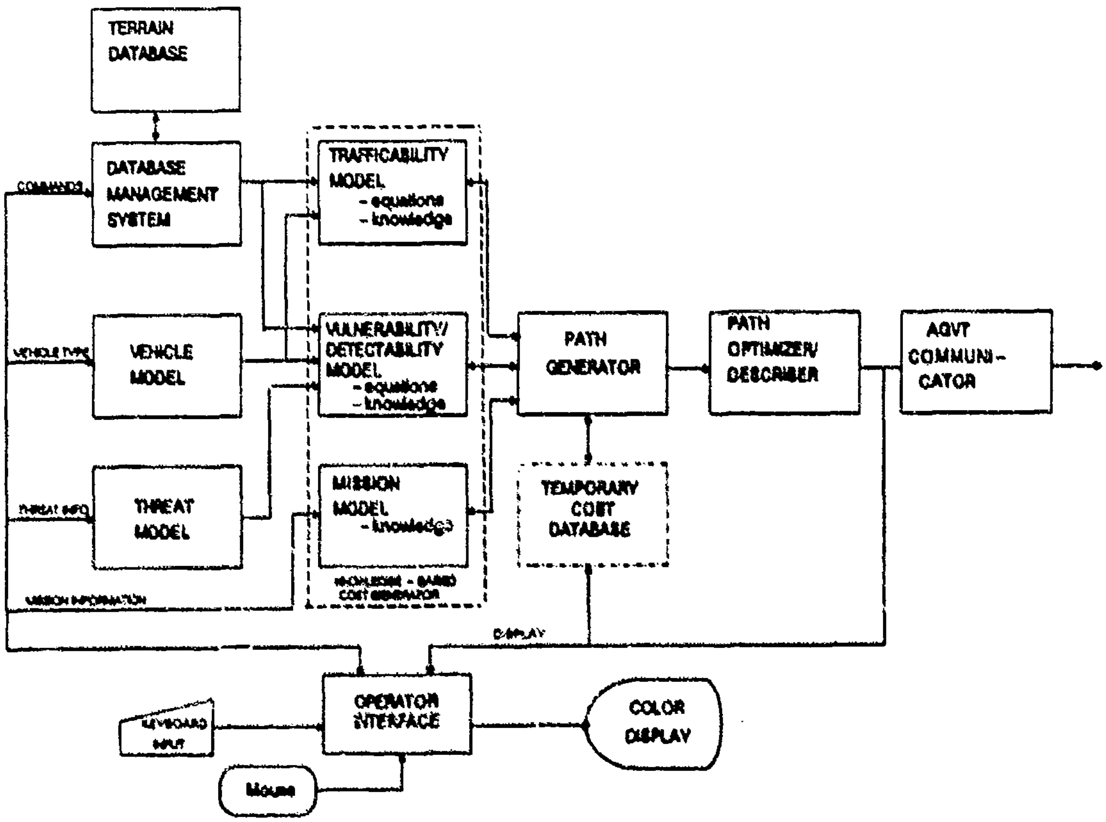

Figure 1: Prototype Global Route Planner System Architecture

The PGRP terrain database has been organized in a cellular hierarchical fashion. Three layers of resolution are used in the database, approximately 10 meters, 30 meters, and 100 meters. Although this results in storage overhead, there is an overall run-time efficiency gained by allowing the planner to focus at the important level. (For instance, a set of detailed street maps should not be used to find your way from New York to Los Angeles, an interstate highway map provides the essential information without additional confusing details).

The vehicle model contains those characteristics important to route planning in a generic model. Also, the specific values to vehicle characteristics are included for the M113 and the HMMWV, with provision for any tracked or wheeled vehicle. This information is provided to the trafficability model and the vulnerability/detectability model at planning time. Likewise, threat types and locations are inserted into the threat model to provide specific information to the vulnerability/detectability model.

The knowledge based cost generator consists of the equations and knowledge embedded in the trafficability, vulnerability/detectability, and mission models. These models provide the basis for determining the time it will take to cross a given cell and the probability of being detected and hit by the enemy when in that cell.

The path generator works in conjunction with the knowledge based cost generator to find the optimal path through the series of cells. It also determines which level of the database needs to be used in evaluating a section of terrain. A modified A* search algorithm is used to find the best route consistent with the mission. Finally, the planned route is smoothed and described through a series of "way-points" for display to the user or automatic communication to an autonomous robotic vehicle.

The system is implemented on a Symbolics 3620 machine, with color display routed to an IBM AT. Symbolics Common LISP is the development environment. Extensive use of "flavors" is made to keep the models as generic as possible and make use of inheritance facilities.

2.1 K wledge Representation Development History

A process similar to the expert system knowledge engineering process was applied to obtain the representations used in PGRP. First, algorithmic approaches to satisfying the various requirements were investigated. Existing terrain data products, mobility models and threat models were surveyed for their interrelationships and capabilities. Terrain databases from Defense Mapping Agency, USGS, ETL, WES, Landsat and SPOT were surveyed. There were specialized terrain databases for use with some mobility models, but there were no completely integrated terrain databases and mobility models which satisfied our requirements for cross-country and on-road speed prediction. Likewise, threat models were not integrated with standard terrain data bases.

In parallel with the model and database survey, informal discussions were held with military personnel responsible for cross country movement planning and military field manuals were reviewed for general techniques, doctrine, and terminology. From these activities, important terms, concepts, and their relationships were grouped and diagramed into a skeleton model of the knowledge, models, and data required for route planning.

Detailed interviews were then held with military cavalry scouts stationed at Ft. Knox, KY with two goals in mind: 1) confirm and enhance the existing skeleton model, and 2) acquire data and knowledge to fill gaps in existing models. The interview process consisted of three major parts: 1) a detailed questionnaire which asked the scouts to assess elements of cover, concealment, mission, terrain, mobility, and overall risk, 2) sample route planning sessions which asked scouts to plan routes through the Ft. Knox range areas given sample operational orders to four different missions and describe their chosen routes and reasons for choosing a particular route, and 3) a general questioning session in which general strategies, techniques, and concepts were discussed and understood.

After the interviews, filtering was done on the data and techniques for isolating general trends and relationships were applied. The basic skeleton model was confirmed and some ad hoc models were also formed to fill gaps between existing models and required information. The sample mission and routes generated by the military scouts were used as a test for the PGRP. Missions were planned and system parameters were adjusted to provide realistic behavior. The computer planned routes still differed from manually planned routes. The final comparison of manually planned routes and routes generated by PGRP will be made through a field exercise. Trained observers will be situated at each threat location. The manually planned routes and computer generated routes will be driven and assessed based on trafficability issues of speed, ride roughness, and ease of navigation and vulnerability issues of cover and concealment.

3.0 Description of the Knowledge-Based Cost Generator

3.1 Top level concepts

Military scouts use an acronym to summarize the important factors in planning routes: METT-T. METT-T stands for Mission, Enemy Situation, Terrain, Time, and Troops. For the Global Route Planner, all of these concepts except "Troops" are important as well. Through the knowledge elicitation process, relationships between these concepts, as well as other related concepts were developed.

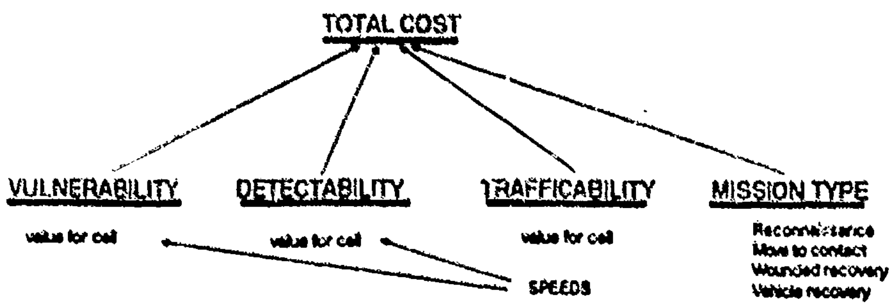

Figure 2: Total Cost is a Combination of the Computed Attributes Weighted by Mission Type

The top level concepts for generating a cost for traversing a cell are shown in figure 2. Total cost is determined by examing three major areas: the VULNERABILITY, DETECTABILITY, and TRAFFICABILITY of a given cell. These values are weighted according to mission types. Answers to the questionaires established relative weighting values for the three major areas based on the type of mission. These weighting values can be tweaked by the system operator. A future enhancement planned for the system is to allow the user to change the weighting values graphically through the mouse interface.

3.2 Trafficability Assessment

Three existing mobility models were surveyed for use in the PGRP. The NATO Reference Mobility Model (NRMM) is the standard NATO model for predicting vehicle mobility characteristics. The main purpose of NRMM is to assess present and potential vehicle designs in specific terrain situations. For a given vehicle, various speed reduction factors are computed for each aspect of a terrain patch, such as the soil conditions, vegetation, tree spacing, stem size, etc. Although this model is the most accurate and comprehensive of those surveyed, it is large, complex, and runs on specific mainframe hardware using non-standard FORTRAN.

The Cross Country Movement (CCM) model is the model used by ETL when generating cross-country movement planning maps. The model also uses speed reduction factors for affecting maximum vehicle speeds. The CCM model has some field validation, however, the model is not as accurate nor as proven as the NRMM. This model is easily adaptable for use on a PC. The CCM has been used in PGRP for making speed predictions for a terrain cell.

A third model surveyed is the Condensed Army Mobility Model System (CAMMS) under development by WES. This model is designed specifically for cross country movement prediction. Again, speed reduction factors are computed for various terrain conditions. Since the model is a derivative of NRMM, high accuracy is expected. Experimental versions of the model are running on a PC. Although this model is best suited for PGRP, it has not been released by WES for general use and s has not been incorporated into PGRP.
Maneuverability knowledge has been based primarily on the ETL general case Cross-Country Movement Model. This model has been slightly augmented to allow on-road speed prediction and stream crossability assessment.

3.2.1 Model Augmentations

The CCM model was augmented to provide predictions of speed for travelling on roads and trails, crossing streams and rivers, and crossing bridges. Data for the augmentation was provided from interviews with the military scouts and review of military field manuals. Scouts were asked to provide the speed used for various road types and when crossing obstacles for each type of vehicle. This data was then used directly in the trafficability model as speed reduction factors.

Also, the three models surveyed do not adequately predict the effects of slope on vehicle speed. In the Ft. Knox area, the slope has a large effect on vehicle speed. Slope for a terrain cell is both preassigned based on the general change in elevation of cells within the larger cell for cross-country movement, and computed on the fly based on the elevations of adjoining cells for on-road movement. Only actual slope computed on the fly has an effect on vehicle speed. The average slope for an area is used to change resolution levels.

3.2.2 Vehicle characteristics

Vehicle information is required by the CCM. Some of the important characteristics for assessing vehicle trafficability are shown in figure 3. Data is provided in PGRP to allow path planning for the M113 vehicle and the HMMWV vehicle.

3.3 Vulnerability/Detectability Assessment

VULNERABILITY and DETECTABILITY are highly related concepts in the Global Route Planner. If a vehicle is not detectable, then it is not vulnerable. If a vehicle is detectable, then it may be vulnerable to a particular threat if it is range of a weapon. Cover and concealment play a fundamental role in establishing the vulnerability or detectability of a given cell. The following concepts are diagramed in figure 4 and explained further below: COVER, CONCEALMENT, ENEMY SITUATION, VULNERABILITY, and VEHICLE characteristics important to vulnerability and detectability assessment.

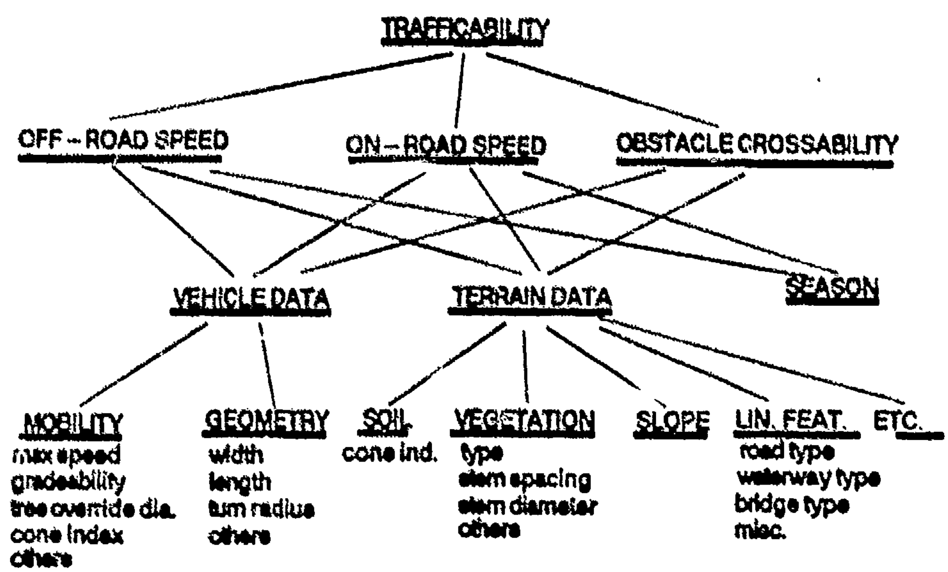

Figure 3: Relationships of Concepts Used for Trafficability Assessment

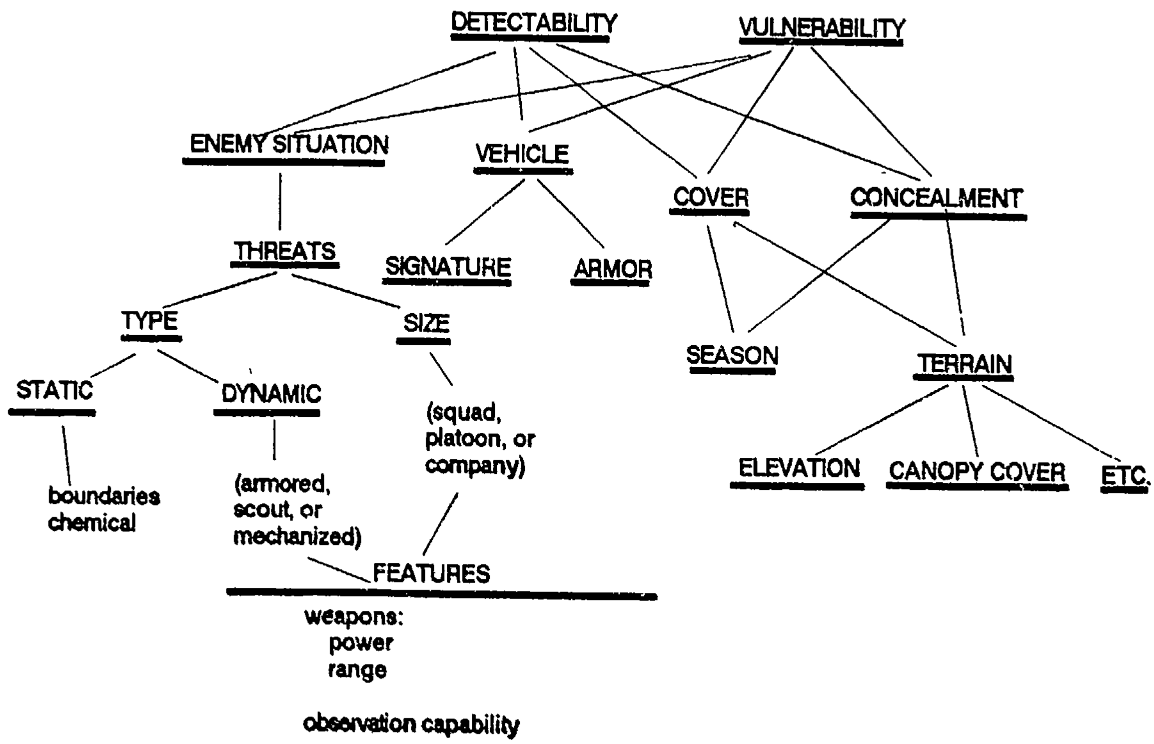

Figure 4: Relationships of Concepts Used for Vulnerability/Detectability Assessment

3.3.1 Cover and Concealment

Cover and concealment are extremely important to scouts when planning routes. Proper cover and concealment should have the effect of discounting any threat, up to 100%.

A "zero-order model" is used for computing COVER and CONCEALMENT due to terrain masking. This model considers only the elevation of the terrain and ignores effects due to the slope of the terrain. Prior to running the planner, each threat is evaluated out to it's range limit. Cells will be masked from the threat if a higher elevation exists between the cell under evaluation and the threat location. All masked cells are assigned a cover/concealment index of 1.0.

Also, all forested areas are evaluated for their cover/concealment potential during the actual planning. Greater tree density will mean greater concealment inside a forest. Granted there are weapons being developed and deployed which seek out the enemy better than before, but we are restricting our attention to threats from the four defined Ft. Knox missions. The cover/concealment index is assigned based on the season (for deciduous forests) and canopy cover, ranging from 0.0 for open ground, to 1.0 for a dense forest.

If a cell has a cover/concealment index of 1.0, then no further calculation of vulnerability needs to take place for that cell (the cell is completely "safe" and vulnerability is set to 0.0).

Calculation of Vulnerability:

If the index is less than 1.0, then the overall vulnerability needs to be calculated using equation (1).

$$\text{vulnerability} = (1 - (\text{prob. of miss}_i)) * \text{speed factor} - \text{c/c index} \quad (1)$$

Note that vulnerability is a function of speed. A maximum speed based on trafficability considerations is computed for a cell. This speed is then used to modify vulnerability. This will tend to make the planner find a fast route for both trafficability and vulnerability considerations. If the vulnerability number is greater than 1.0, it is set to 1.0. If the number is less than zero, it is set to 0.0.

3.3.2 Enemy Situation

ENEMY SITUATION is based on THREATS. There are STATIC THREAT and DYNAMIC THREAT types, each with characteristic THREAT SIZE, and THREAT FEATURES (dependent on size and type). This is further expanded in figure 4.

ENEMY SITUATION is evaluated with each threat concentrated at a point and the overall size of the threat being a combination of all of the units. The enemy position is modified from the user input to the highest terrain point in the local area, where the local area is determined from the force size.

A probability of hit function is developed for each dynamic threat type. Data for the hit functions are derived from the interview process and from references [1] and [2]. Bayesian statistics were used to combine probabilities of "miss" from more than one enemy unit, up to platoon and company levels. A straight line degradation of hit probability was then assumed and results extrapolated from 100% to 0% hit probability with range. The actual hit probability may not be linear with range, however, actual hit probability functions can be easily handled by the existing structure of the PGRP. Probability of "miss" was then defined to be (1 - prob. of hit).

The entire process of enemy situation evaluation forms a flattened "cone" of hit probability for each type of dynamic threat when described as motorized/armored/scout and squad/platoon/company. This cone is centered about the location of the threat. The cone has straight sides for a squad threat function and polynomial sides for platoon and company threat functions. When influence is felt from more than one threat, the overall probability of miss is

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1 United States Army Field Manual 7-7, The Mechanized Infantry Platoon and Squad, 9/30/77

2 "Modern Soviet Combat Tanks," Steven Zaloga, Osprey Publishers, 1984.

given by the product of the two independent threat functions.

3.3.2.1 Speed Factor

Probability of miss for dynamic threats is also a function of vehicle speed. This effect has been assumed to be independent in a probabilistic sense from the effect of range. Thus a probability effect based on speed can be considered separately from the range effect. For a "stadia rangefinder" system, an exponential fall-off of a hit coefficient with speed is a reasonable ad hoc approach. A translation is then made to miss coefficient vs. speed. This is a factor between 0 and 1.0. This factor should only be applied for longer range shots, since speed has little effect on miss probability for short range shots

3.3.2.2 Static Threats

Static threats are also analyzed by PGRP. These threats include minefields, and chemicals. Static threat boundaries are marked with a line or polygon. This process forms "NOGO" regions for static threats. These regions are automatically rejected by the planner. Recon missions can be handled through the probability of staying undetected function.

Probability of "detection" (or going "undetected") is assumed to have a similar function as probability of hit/miss, with a similar method of combining multiple threats. Although the effects of noise are not yet included, they are easy to add to the basic function of detectability. The overall detectability is found using equation (2). Note that the effect of speed has been eliminated from consideration.

$$\text{detectability} = (1 - (\text{prob. of undetected})) - \text{c/c index} \qquad (2)$$

If this number is greater than 1.0, it is set to 1.0. If the number is less than zero, it is set to 0.0. (Again, if c/c index is 1.0, no further calculation is required as detectability = 0.0).

4.0 The Planning Process

At run time, the user sets up the mission information, including vehicle type, starting point, destination point, waypoints, mission type, and threat types and locations. The planner first evaluates the terrain surrounding each threat for terrain masking. Masked areas are displayed as an overlay to the map. The A* search algorithm then works with the knowledge-based cost generator to compute a total cost for crossing the cell under evaluation. The heuristic used is the time to travel from start to destination in a straight line at maximum vehicle speed averaged with a weighted cost to get to the current cell. This heuristic could overestimate the cost, but has shown very robust performance to date. In the first and last 500 meters, the A* algorithm is converted to a complete search so that the optimal path near the starting and destination points is guaranteed. The planner will move up and down in resolution levels to accomodate more detailed information when trying to find narrow paths through hilly areas (as determined by average slope) or around streams.

The total time required for computer-based planning is about 5 minutes, comparable to the time required by military scouts planning the same missions.

5.0 Problems Encountered

There are no integrated mobility model/terrain database systems available for cross-country and on-road movement prediction for robotic vehicles. Each mobility model requires it's own special purpose terrain database organized in a unique format. Some of the terrain aspects required for accurate movement prediction, such as tree spacing and stem diameter, are not readily obtainable from existing data sets or maps so that elaborate mechanisms are required to extract the information from aerial photographs or terrain reconnaissance.

Since the maximum rated vehicle speed is used, esisting mobility models tend to overestimate the speed which can be achieved in a terrain segment. Also, existing mobility models are not designed with cross-country movement prediction in mind. Factors which are important for vehicles travelling cross-country, such as side slope vs. speed relationships, need to be included in existing models.

Terrain information is not readily available in the required forms for all areas of interest, either. Terrain data bases tend to be excellent for places such as Fulda, West Germany but non-existent for Camp Grayling, MI. Also, information such as stream velocities and depths are not usually available (and are highly seasonal). Terrain data bases with the information required by the mobility models are needed to test autonomous robotic vehicles in a controlled yet realistic environment.

Some hope exists that the CAMMS system in conjuction with the Tactical Terrain Analysis DataBase (TTADB) will result in a consistent relationship between mobility modelling and terrain databases. This project is an ongoing effort by the U.S. Army.

6.0 Conclusions

A route planner has been developed for robotic vehicles. The planner supports a variety of mission types for at least two vehicles. Routes are planned according to methods used by military scouts. An object-based representation scheme using Symbolics Common Lisp has been used effectively to describe relationships between concepts required for evaluating Mision, Enemy, Terrain and Time.

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IRIS -- An Intelligent Robot Insertion Expert System

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Huntsville, Alabama 35805

ABSTRACT

Teleoperated manipulators working in an unstructured environment can perform a variety of tasks. Most maneuvers are, however, similar to the classical peg-in-the-hole problem in that the manipulator must be put in the proper postion and orientation prior to completing the task. Typical examples include inserting parts, connecting couplers and opening drawers. To maneuver the manipulator to the desirable position and orientation by teleoperation is non-trivial, and requires considerable operator training. The present work examines the possibility of exploiting AI technology to tackle this problem.

IRIS is a prototype expert system that provides a solution to the peg-in-the-hole problem. The expert system can successfully "dock" the robot with a hole in the taskboard, thereby completing the insertion process. IRIS is a rule-based, data driven, forward chaining expert system. Two sensors are required to provide input to the system: a vision system that can discern the taskboard and the hole and a ranging sensor that provides the range information. Preliminary investigation demonstrated that as long as the taskboard is placed within the work envelope in some reasonable orientation, the system can complete the mission successfully. At the time of this writing, collision avoidance is not yet implemented.

It is felt that when completed such an expert system will find application in a number of areas, especially when repetitive tasks must be conducted in an unstructured environment.

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PEDAGOGICAL ISSUES IN DEVELOPING A MAN-MACHINE INTERFACE FOR AN INTELLIGENT TUTORING SYSTEM

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ABSTRACT

The use of expert and knowledge based systems have not always met with the success in the user environment as was promised or expected during the development and operation in the laboratory environment. As knowledge based systems expand in complexity and achieve extended operation in the user environment, the man-machine interface (MMI) function becomes a major issue in developing effective and usable systems. In fact the MMI consideration has become the hidden agenda in the effective application of knowledge based systems.

A case in point is the MMI needs associated with developing an effective Intelligent Tutoring System. Reported here are the results of an early research effort on major MMI issues associated with developing an Intelligent Tutoring System used as an embedded training device. The student interface or MMI is included as a major sub-element of the tutoring system and is considered an integral part of the system during development and assessment of user needs.

1.0 INTRODUCTION

Research has shown that several specific factors have contributed to the less than expected use and performance of expert systems when placed in the user environment. A major factor is the Man-Machine Interface (MMI) associated with the delivery system. In many instances the MMI function was considered only after the basic structure of the expert system has been established and the methodology for expert operation had been demonstrated. In cases with the most reduced user acceptance are instance where the MMI function was added on after the major development effort was completed or an existing interface was expanded to meet expected user requirement. In short the "User Friendliness" promised or required for effective operation of the expert system in the user environment was not delivered.

The human interface aspects of knowledge based systems must be given a different emphasis than the traditional man-machine or man-computer human engineering. The interface issue becomes critically important long before the system begins to make the transition from the development environment to the user environment. A case in point is a unique requirement in the development of knowledge based expert systems. The present state-of-the-art in knowledge acquisition requires the knowledge engineer to become intimately familiar with the task and the problem solving approach of the human expert and the environment of the user of the knowledge based expert system. This is the first and a critically important interface operation in the expert system development process. This early operation should serve as a pointer to the uniqueness and importance of the man-machine operation in knowledge based systems development and application.

The issues surrounding MMI in general are complex and too extensive to be treated in detail in a single research and development effort. The most effective alternative is to restrict the domain of interest with specified limits on the scope of the interface application. The domain of interest here is MMI issues associated with knowledge based systems. However, given an appropriate set of assumptions, the purpose of the system here is "to provide a training function sufficient for maintaining proficient knowledge and skill levels necessary for operating a specific system or process". Operationally, the system must provide sustainment training to maintain critical skill levels and also include maintaining knowledge levels about the system operation requiring the capabilities of an Intelligent Tutoring System.

A distinction is made here between what may be considered traditional MMI characteristics and the special interface characteristics for knowledge based intelligent tutoring systems. The term Intelligent-man-machine-Interface (IMMI) will be used for the latter.

Some research efforts treat the operation of the system behind the interface as a black box and attributes all the operational characteristics of the system to the interface requirement. The approach used in the research reported on here is some what different. It is instructive to provide a specific context for the IMMI operation. The IMMI will operate in a tutoring system that performs the "functional equivalent" of a human tutor. This functional equivalent has been accomplished in the past with a wide variety of teaching aids, as characterized by early Computer Aided Instruction (CAI) to the more recent teaching with Intelligent Tutoring Systems.[1,2]

2.0 COMPUTER AIDED INSTRUCTION

Since the earliest introduction of computers into education the emphasis has been that of a device that interacts directly with the student as opposed to an assistant to the human teacher. The three general approaches to the use of computers in education include: a free style which allows the student free use of the machine in areas such as programming; the second instructional approach uses game and simulations; third, CAI became the bases of student-machine interaction. The first two educational uses of the computer in education made assumptions that learning problem solving methods took place as a side issue during student use of the computer. Computer-aided instruction was a departure from the first two activities in that the computer was used to provide some control and direction to the learning process.

Through out the early use of computers in education the emphasis was on programs and computer operation with minimum attention focused on the student-machine interface needs and requirements. While the goal of CAI is to build instructional programs that incorporate well prepared subject material, much of the early CAI operation were drill and practice monitors with pre-stored answers.

3.0 INTELLIGENT TUTORING SYSTEM

The major sub-elements associated with a functional equivalent of a human tutor or an intelligent tutoring system are shown in Figure 1. The scenario generator (Module A) generates a task or scenario that is presented to the student operator (Module B) through the MMI (Module H). Concurrently the scenario is presented to the expert in the expert solutions module (Module C). The choices and related actions of the student in response to the scenario is transmitted to the compare solutions module (Module D) via the interface. The appropriate action taken by the expert is compared with the student action in the compare module. The differences between the appropriate action generated by the expert and the student action is generated in the compare module and transmitted to the deficiencies module (Module F).

A model of the student's deficiencies associated with the present scenario operation is generated in the deficiencies model module (Module F). Elements of the deficiencies model is transmitted to the student model for developing particular knowledge about the individual student and a history of the student's performance. In addition, information generated by the deficiencies model is transmitted to the tutoring strategy module (Module G). With information about deficiencies in performance on the present scenario and background and history of the student's performing from the student model, an appropriate strategy for the student is generated by the tutoring strategy module (Module G).

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1 Kears, Greg (ED), Artificial Intelligence & Instruction, Application and Methods, Addison-Wesley Publishing Company, Reading, Mass., 1987.

2 Wenger, Etienne, Artificial Intelligence and Tutoring Systems, Morgan Kaufman Publishing Company, Reading, Mass., 1987.

An appropriate tutoring strategy includes specific problems or tasks for the student to accomplish to improve performance or correct identified deficiencies. The task area assignments module (Module I) receives information from the tutoring strategy module and identifies the specifics of a required task. The specifics of the required task are transmitted to the scenario generator. The new scenario is transmitted to the student and the expert and the process as previously described is repeated. The process continues until the skills of the student are developed to a predetermined level or the expert solution level. Further information on this structure for a tutoring system is reported by Holmes.[1]

4.0 PEDAGOGICAL ISSUES FOR IMMI

4.1 CONTEXT FOR DESIGN

The specifics of the design, development and implementation of an IMMI must generally be stated in context of the domain of application. The issues discussed and presented here for an IMMI will be in the general context of the tutoring system shown in Figure 1, specifically Module H, the student-machine interface. The strucutre of the IMMI is stated in terms of a modular approach, consistent with the approach used in developing the Intelligent Tutoring System. The over all structure is stated as: (1) isolate the capabilities of the IMMI into distinct modules; (2) abstract all domain dependent information in an explicit knowledge base; (3) identify an explicit structure for the user model(s).

4.2 MODULAR STRUCTURE FOR IMMI DEVELOPMENT

As used in this research effort, a functional model of the modular IMMI system is shown in Figure 2. The term "User Model" is used here to indicate representational methodology and knowledge about the user of the system that will be necessarily different form the student model identified in Figure 1. The knowledge base contains domain dependent information and knowledge for user model operation. Data translators are defined as devices used to translate system generated data to a specific representational modality. The particular modality selected for interface operation will be determined by the needs and desires of the user as contained in the user model. The number of data translators included in an IMMI system indicates the scope of operations and interactive power for the community of users.

The data translators identified as modules three through five, i.e., text, graphics and speech synthesis are used to indicate the range of individual information communication options available. The data translator identified in module six as a symbol generator operates in one of two modes: (1) generates independent symbols from system input data or; (2) combines the modalities of the other data translators to produce specific symbols to communicate with the user.

The combination of text and graphics would be most appropriate in some instances while text and speech would be most effective in other cases. The particular modality is selected according to the ability to transfer useful information. The selection is made depending on what is considered most effective as established by the user representation model.

5.0 USER DEPENDENT KNOWLEDGE

In all aspects, an IMMI in an integral part of a user conscious system. In this aspect Berry has identified knowledge that a user conscious system should contain about the user.[2]

(1) What competence does the user have with the system?

(2) What level of domain expertise does the user possess?

(3) What are the interest, values and goals of the user?

(4) What are the expectations and assumptions of the user?

(5) What is the preferred method of interaction?

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1 Holmes, Willard M., "A Structure For Developing A Domain Specific Intelligent Tutoring System For Maintaining Proficient Skill Levels For Weapons System Operation" in Proceedings of Conference on New Training Technology, The national Science Center for Communication and Electronics, Ft. Gordon, GA, April, 1988.

2 Berry, D. C., and Broadbent, D. C., "Expert Systems and the Man-Machine Interface" (Part 1), Expert systems, 3(4):228-232, October, 1986.

(6) Modeled understanding of how the system works.

The user knowledge base will include more than just knowledge about the user. Knowledge about certain aspects of the domain of the tutoring system operation is required. This will result in a shared knowledge base or a set of knowledge elements in both the user and the student related knowledge-bases. To the extent feasible, a shared knowledge base approach is preferred.

5.1 USER MODELS

The above items point to maybe what constitutes a minimum knowledge base for generating a desired knowledge representation for the user. The user knowledge base and the user model determines the appropriate action. Recent research conducted by Borden et al.[1] point out that user models are typically represented in one of the following forms:

(1) Parametric, in which a set of values is identified to characterize the user for a given task;

(2) Discrete-Event, in which the command or keystroke sequence is massaged into a finite-state or finite-context model;

(3) Frame-like, in which the domain knowledge is used to identify explicitly his performance with each concept or action;

(4) Expert Difference Modeling, which compares performance with a pre-determined standard;

(5) Bad Plan Detection, which recognizes instances of pre-stored behavior sequence which suggest unfamiliarity with a concept;

(6) Candidate Model Search, which can lead to a successful finite state methodology in restricted domains;

(7) Concept Use Frequency Analysis, to provide evidence of areas in which user performance is lacking.

A characteristic that is common to all the above approaches to user modeling is that either directly or indirectly the model is developed using measurements of the user's performance.

6.0 CONCLUSION

Noticeably missing from this discussion is any mention of voice recognition, color generation, and specific input devices. During the early phases of research on this project, demonstrations and reported research on voice recognition pointed to two conclusions:

(1) Voice recognition is still deeply embedded in research and not readily available for application that requires realtime operation and involves a large vocabulary;

(2) Performance is reduced in applications where the user community involves a wide range of user voice characteristics and under widely varying conditions, i.e., relaxed environment and highly stressful environments.

Similar comments can be made about the use of color in tutoring and the transfer of expertise. Research is still needed to establish what is the best combination of colors and how information should be presented with color combination to achieve the best learning environment. It is not clear that the added cost and complexity achieves comparable increase in achieving the intended goals.[2]

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1 Borden, P., Griffith, P., and Somers, ?., An Analysis of Pedagogical Issues In Developing an Intelligent Tutoring System Student-Machine Interface, MICROEXPERT SYSTEMS, Inc., 27007 Ventura Blvd., Suite 210, Calabasa, CA 91302, Final report for U. S. Army MICOM RD&E Center, Contract DAAL03-86-D-0001, November 23, 1987.

2 Badler, N. I., Marcus, M., and Joshi, A. K., "Human-Computer Inteaction" Computer and Information Science, University of Pennsylvania, Course notes, Ft. Leavenworth, KA, March 8, 9, 10, 1988.

The input devices considered for this particular application environment will be limited to: mouse, keyboard, joystick and multi-level switches.

The IMMI is being developed concurrently with other sub-modules of the tutoring system indicated in Figure 1. Some of the system sub-modules are being developed by different task groups. For uniformity and ease of integrating the sub-modules, all development efforts are using Inference Corporation's Automated reasoning Tool (ART) and Symbolics work stations.

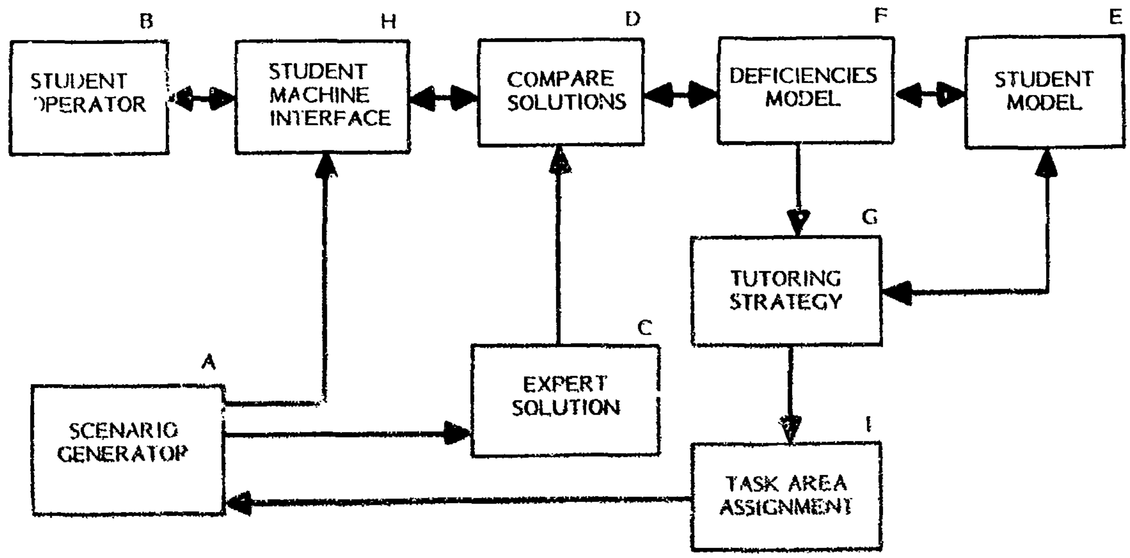

Figure 1. INTELLIGENT TUTORING SYSTEM FUNCTIONAL MODEL.

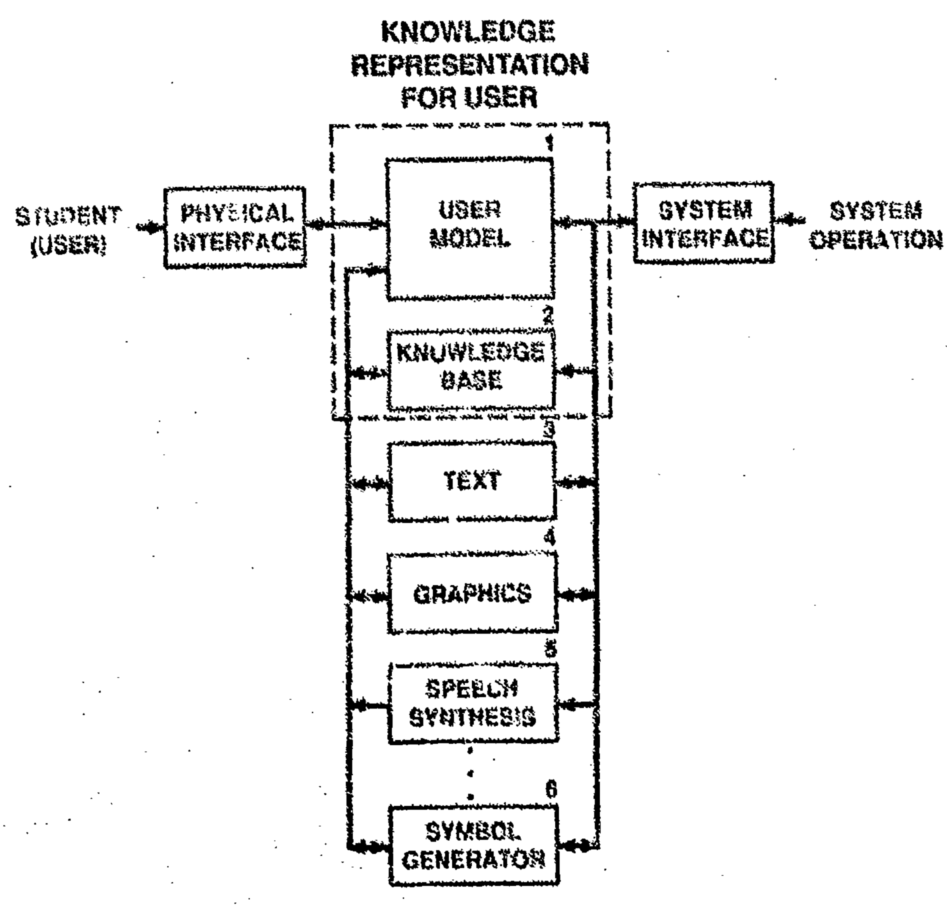

Figure 2. FUNCTIONAL MODEL FOR AN INTELLIGENT MAN-MACHINE INTERFACE.

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